Commercial environmental forestry in low-to-medium rainfall areas:
A preliminary spatial analysis of expected environmental benefits to aid selection of a focus research area

Albert I. J. M. van Dijk, Jenet Austin, Warrick R. Dawes and Peter B. Hairsine

Prepared for the Commercial Environmental Forestry project, funded by the Natural Heritage Trust

Commercial Environmental Forestry report CLW/01

This report has previously been published as CSIRO Land and Water Technical Report 10/04

CSIRO Land and Water Client Report
February 2004
Commercial environmental forestry in low-to-medium rainfall areas:

A preliminary spatial analysis of expected environmental benefits to aid selection of a focus research area

Albert I. J. M. van Dijk, Jenet Austin, Warrick R. Dawes and Peter B. Hairsine

Prepared for the Commercial Environmental Forestry project, funded by the Natural Heritage Trust

CSIRO Land and Water, Canberra
Technical Report 10/04

February 2004
Executive Summary

Tree plantations on agricultural land in Australia’s low-to-medium rainfall areas may, through the reduction of groundwater recharge and thence stream salt loads provide important environmental benefits. If markets or purchasers for these environmental benefits can be found, the plantations may also deliver acceptable financial returns. When determining overall environmental benefit or dis-benefit, reductions in catchment water yield resulting from tree planting and time lags in delivering salinity reductions need to be included. Forest productivity and regional processing and transport infrastructure will also affect viability.

CSIRO’s Commercial Environmental Forestry (CEF) project is developing a blueprint for a decision support framework that takes into account these environmental and commercial aspects. The project has undertaken a preliminary analysis of site conditions to help select a focus research area where the framework is to be developed and tested. This report describes the biophysical analyses that formed the basis for this selection.

A shortlist of prospective research focus area was provided by State agencies based on preliminary criteria set out by the project team. These criteria included:
- largely situated in a low-to-medium rainfall zone (500–800 mm y\(^{-1}\));
- designated National Action Plan for Salinity and Water Quality priority catchment;
- significant decrease in stream salinity expected after afforestation;
- dominated by local groundwater flow systems (GFSs);
- intermediate-size catchment (i.e. 500—5000 km\(^2\));
- close to commercial forest growth levels suggested by rainfall and soils;
- existing wood processing facilities within 150 km; and
- high likelihood of sufficient landholder uptake.

The State agencies proposed six regions in the Southeast Murray-Darling Basin (ranging in size from 646 to 3,742 km\(^2\)): the Upper Little River, Boorowa-Jugiong, Kyeamba-Tarcutta and Billabong catchments (all in New South Wales); and the Bet Bet Creek and South West Goulburn catchments (Victoria).

These six areas were further analysed to determine which would most effectively support project research. The assessment criteria were:
- reduced stream salinity is likely to occur within 15 years after afforestation (representing a useful time horizon for economic analysis); and
- forest productivity is reasonable or good (indicated by modelled mean annual increments for \textit{Pinus radiata} of 10–15 and >15 m\(^3\) ha\(^{-1}\) y\(^{-1}\), respectively).

The likely change in catchment stream flow and stream salinity 15 years after afforestation was calculated for each catchment, expressed as change per hectare of plantation established on non-forested land. The BC2C model (Dawes and Gilfedder, in review) was used because it incorporates the latest understanding of local ground water systems and climate-vegetation water use relationships. Within the catchments the areas with reasonable and good forest productivity were identified using the model results of Booth et al. (in press).

Based on the model results, the greatest opportunities for commercial environmental forestry are expected in the Southwest Goulburn catchment. In this region, a total of 463 km\(^2\) (12% of total area) showed potential for a combined commercial and environmental forestry (CEF) approach.

A spatial comparison of the areas with greatest forest productivity and the areas with greatest stream salinity reductions suggested that site suitability is the most important constraint to CEF. The main limitation appeared to be the often long time lag between afforestation and stream salinity reduction. Also, the relative reduction of salt load discharge into the stream must be
greater than the loss of stream flow originating from other sources (overland and near surface flow).

Future work will address these constraints, as well as make better use of available biophysical data and develop production estimates for trees that are more suitable for this environment than *Pinus radiata*. Furthermore, the prediction of environmental impacts and forest productivity will be integrated within an economic analysis framework that also takes into account the spatial distribution of transporting and processing infrastructure.
# Table of Contents

1. Introduction ................................................................................................................................. 2  
   1.1. Background ............................................................................................................................ 2  
   1.2. Project context ....................................................................................................................... 3  
   1.3. Structure of this report ........................................................................................................... 3  
2. Methodology .................................................................................................................................. 4  
   2.1. Overall approach and pre-selection of focus catchments ....................................................... 4  
   2.2. Modelling impacts on stream flow and salinity ..................................................................... 6  
   2.3. Modelling potential forest productivity ................................................................................. 8  
3. Results ......................................................................................................................................... 10  
   3.1. Overall results ...................................................................................................................... 10  
   3.2. Results for the Southwest Goulburn catchment ................................................................... 11  
4. Discussion ................................................................................................................................... 14  
   4.1. Change in water yield .......................................................................................................... 14  
   4.2. Change in stream salt loads and salinity .............................................................................. 15  
   4.3. Physical constraints to CEF ................................................................................................. 15  
5. Conclusions ................................................................................................................................. 16  
   5.1. CEF opportunities in the six pre-selected catchments ......................................................... 16  
   5.2. Main uncertainties and needs for development .................................................................... 16  
Acknowledgements ......................................................................................................................... 18  
References ....................................................................................................................................... 19  
Glossary ........................................................................................................................................... 21
1. Introduction

1.1. Background

Realising the potential environmental benefits of establishing plantation forests in Australia’s low-to-medium rainfall areas (400–800 mm y⁻¹) can help to make these enterprises commercially attractive. Clearing of native vegetation and its replacement with agricultural land uses has in many areas led to increased recharge of the groundwater system. The increased groundwater flow has mobilised salt that is now degrading both land and water resources. Returning deeper rooted and more permanent vegetative cover will decrease groundwater recharge and so can mitigate this process. The associated ‘salinity benefits’ can provide an incentive for the expansion of plantation forests in these drier areas, where it currently is not widespread and typically commercially marginal or not profitable.

Commercial environmental forestry (CEF) to mitigate stream salinity has two important constraints related to the reduction of stream runoff, and the time lag between plantation establishment and stream salinity change, respectively. Stream runoff is reduced upon afforestation because forest generally uses more water than cropland (e.g. Zhang et al., 2001). This may have adverse impacts on the availability of water downstream. The rate at which the groundwater flow system (GFS), and through this ultimately stream salinity, responds to reduced recharge depends on physical properties of the groundwater system that cannot be manipulated. For instance, in landscapes where groundwater travels a long distance between recharge and discharge areas (e.g. >50 km in the case of regional GFSs), the clearing of native vegetation that took place more than a century ago has just started to increase stream salinity. For the same reasons changing land use to reduce groundwater recharge in these landscapes will take a very long time to produce observable reductions in stream salinity. This places these environmental benefits beyond the scope of present economic decisions. In faster responding GFSs, the reduction in salt loads can occur more rapidly but will still lag behind the reduction in catchment water yield. Therefore, salt concentration (but not total annual salt discharge) will increase initially and will eventually approach an equilibrium value that can be above or below the original value, depending upon the physical attributes of the environment (Vertessy et al., 2003). Well-targeted establishment of new forests in areas where the reduction of salt discharge is greatest and most rapid and runoff reduction is minimised has the potential to make CEF possible.

There are other potential environmental benefits to be gained from the CEF approach. These include carbon sequestration, soil conservation and rehabilitation, decreased land salinity, reduced stream nutrient and sediment loads, enhanced landscape diversity, ecological connectivity and biodiversity. There are also some potential economic and social benefits (Alexandra, 2002).

The viability of CEF is further influenced by forest production rates and transport and processing infrastructure. Forest growth rates in low-to-medium rainfall areas are often limited by water availability. Some suitable forestry areas lack an established forest industry and associated transport and processing infrastructure. This imposes additional constraints on the viability of CEF.
1.2. Project context

In October 2003, the Department of Agriculture, Fisheries and Forestry together with CSIRO initiated the Commercial Environmental Forestry (CEF) project through the Natural Heritage Trust program. The CEF project aims to develop and optimise forestry systems for profitability, environmental benefits and regional community development in low-to-medium rainfall zones typical over much of Australia. Subsidiary aims are to quantify the environmental benefits of plantations, to provide greater certainty around prediction of plantation productivity, and to ultimately increase financial returns for growers and processors. The project will support these goals by assimilating knowledge available within the different scientific disciplines in a blueprint Scenario Planning Investment Framework (SPIF). The purpose of this framework is to enable a spatially explicit economic analysis of opportunities for environmental forestry investment in low-to-medium rainfall areas.

The SPIF framework will initially be developed and tested in a focus area where CEF forestry is likely to be viable, taking into account the various constraints outlined above. The selection of this focus area was carried out in the initial stages of the project. Using preliminary criteria set out by the project team the State agencies of Victoria and New South Wales proposed a total of six catchments for further analysis. For each we carried out a spatially explicit modelling exercise to identify areas with both environmental benefits and good forest productivity. The present report describes and discusses this analysis, which informed the eventual selection of a research focus area.

1.3. Structure of this report

The study methodology is described in the following section. It outlines the criteria based on which the first selection of six catchments was made and describes the approach followed in the spatial analysis of environmental benefits and production rates expected after afforestation. The results are presented in Section 3 and discussed in Section 4, in which the expected changes in catchment runoff, stream salt loads and concentrations are presented for each of the six catchments. For the most promising catchment, a more detailed spatial analysis was made to identify the main constraints for CEF. The uncertainties and weaknesses in the analysis are also discussed. Finally, conclusions and directions for improvement are given in Section 5.
2. Methodology

2.1. Overall approach and pre-selection of focus catchments

A shortlist of prospective research focus area was provided by State agencies based on preliminary criteria set out by the project team. These biophysical, institutional and social criteria were aimed at optimising the likelihood of achieving a successful pilot planting and included the following:

- Largely situated in a low-to-medium rainfall zone (500–800 mm y\(^{-1}\)).
- Designated as a National Action Plan for Salinity and Water Quality (NAP) priority catchment. This increased the chance that a CEF-based Catchment Investment Strategy might attract NAP funding.
- Significant decrease in stream salinity expected after afforestation in terms of the Murray Darling Salinity Management Strategy, i.e. compared to current estimates the predicted change in average daily salinity in the Murray River at Morgan (expressed as electrical conductivity, EC) would be at least 0.1 µS cm\(^{-1}\) within 100 years (MDBC, 2001) (this also introduced the requirement that the area was situated within the Murray-Darling Basin).
- Dominated by local groundwater flow systems (GFSs). The response time of GFSs causes a time lag between land use change and the realisation of environmental benefits. The presence of local, faster responding GFSs increase the likelihood of a salinity benefit (credit) within an economic timeframe.
- Intermediate-size catchment (tentatively defined as 500—5000 km\(^{2}\)). This was taken to represent a useful compromise between, on the one hand, the greater likelihood for smaller catchments that afforestation leads to observable salinity reductions at the catchment outlet and, on the other, the greater variation in biophysical properties expected for larger catchments, and therefore the greater likelihood that substantial areas suitable for CEF could be identified.
- Close to commercial forest growth levels expected. For this reason, the higher end of the above mentioned rainfall range was preferred and soils suitable for forestry needed to be present within the area.
- Existing wood processing facilities within 150 km of the area; this was tentatively assumed to be the maximum distance over which log haulage was considered economic.
- High likelihood of sufficient landholder uptake to drive the project.

Based on these criteria, State agencies in New South Wales and Victoria proposed six regions in the Southeast Murray-Darling Basin for further analysis. These were the Upper Little River, Boorowa-Jugiong, Kyeamba-Tarcutta, and Billabong catchments in New South Wales, and in Victoria the catchments of the Bet Bet Creek (North Central Catchment Management Area) and Southwest Goulburn (Goulburn-Broken Catchment Management Area). The location of the six pre-selected catchments is shown in Figure 1 and some of their hydrologic characteristics are listed in Table 1 (note that the term catchment is used somewhat loosely here; some of these regions receive water from upstream or have parts draining into different river systems).
The catchments vary by a factor of six in area, from the 646 km² Bet Bet Creek catchment to the 3,742 km² Southwest Goulburn catchment, but otherwise they have comparable characteristics (Table 1). The area not yet covered by forest ranges between 56 and 94% (the 250 m by 250 m cells are classified as forest if more than 20% of the area is covered by woody vegetation). The area underlain by local to intermediate GFSs – that is, in which the average distance between groundwater recharge and discharge points is <50 km – is substantial in all six catchments (>67%). The average annual rainfall (688–720 mm y⁻¹) and the range found within the catchments are very similar for four catchments, whereas the Bet Bet Creek catchment is drier (580 mm y⁻¹) and the Kyeamba-Tarcutta catchment somewhat wetter (839 mm y⁻¹).

Table 1. Hydrological characteristics of the six pre-selected catchments.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Bet Bet Creek</th>
<th>Southwest Goulburn</th>
<th>Upper Little River</th>
<th>Boorowa-Jugiong</th>
<th>Kyeamba-Tarcutta</th>
<th>Billabong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>646</td>
<td>3,742</td>
<td>1,179</td>
<td>3,173</td>
<td>2,311</td>
<td>2,981</td>
</tr>
<tr>
<td>% in 400–800 mm y⁻¹ range</td>
<td>100%</td>
<td>82%</td>
<td>97%</td>
<td>94%</td>
<td>51%</td>
<td>86%</td>
</tr>
<tr>
<td>% not forested *</td>
<td>73%</td>
<td>66%</td>
<td>56%</td>
<td>94%</td>
<td>66%</td>
<td>85%</td>
</tr>
<tr>
<td>% local or intermediate GFS</td>
<td>75%</td>
<td>77%</td>
<td>100%</td>
<td>100%</td>
<td>89%</td>
<td>67%</td>
</tr>
<tr>
<td>Rainfall (mm y⁻¹)</td>
<td>580</td>
<td>688</td>
<td>715</td>
<td>720</td>
<td>839</td>
<td>680</td>
</tr>
<tr>
<td>Rainfall range (mm y⁻¹) **</td>
<td>500-730</td>
<td>520-1140</td>
<td>650-810</td>
<td>610-910</td>
<td>570-1390</td>
<td>490-1010</td>
</tr>
</tbody>
</table>

* defined as 250 by 250 m cells having <20% estimated woody vegetation cover

** minimum and maximum average annual rainfall within the catchment (rounded to the nearest 10 mm y⁻¹)

The catchments vary by a factor of six in area, from the 646 km² Bet Bet Creek catchment to the 3,742 km² Southwest Goulburn catchment, but otherwise they have comparable characteristics (Table 1). The area not yet covered by forest ranges between 56 and 94% (the 250 m by 250 m cells are classified as forest if more than 20% of the area is covered by woody vegetation). The area underlain by local to intermediate GFSs – that is, in which the average distance between groundwater recharge and discharge points is <50 km – is substantial in all six catchments (>67%). The average annual rainfall (688–720 mm y⁻¹) and the range found within the catchments are very similar for four catchments, whereas the Bet Bet Creek catchment is drier (580 mm y⁻¹) and the Kyeamba-Tarcutta catchment somewhat wetter (839 mm y⁻¹).
The environmental impacts and forest production rates were modelled for the six pre-selected catchments to assess and compare the likelihood for successful CEF. The latest understanding of GFSs and climate-vegetation water use relationships as incorporated in the BC2C model (Dawes et al., 2004) was used to estimate the environmental effects of afforestation on stream flow and salinity within the six catchments. These results were combined with spatial estimates of forest productivity produced by the PROMOD model (Booth et al., in press). The two models and the input data used are further discussed in the next section. To allow the biophysical modelling, two additional criteria needed to be met:

- The area coincided with one or more well defined (sub-) catchments because modelling is done on a (sub-) catchment basis (in this report, we pragmatically define the pre-selected areas as catchments, and their component catchments as sub-catchments).
- The soils and groundwater flow systems (GFSs) in the area were understood and maps of their properties available for model parameterisation.

These requirements could be met for all six pre-selected catchments. The model results were analysed and interpreted to assess the likelihood of successful CEF establishment. The assessment criteria used in this analysis were:

- Reduced stream salinity can be realised within 15 years. In consultation with experts, a 15 year period was considered a time horizon useful for making economic decisions; and
- Forest production rates are predicted to be reasonable or good. For the present study, these rates were defined as expected mean annual increments for Pinus radiata of 10−15 and >15 m³ ha⁻¹ y⁻¹, respectively.

2.2. Modelling impacts on stream flow and salinity

The Biophysical Capacity to Change (BC2C) model (Dawes et al., 2004; Dawes and Gilfedder, in review) has been developed to predict the impact of land use change on stream flow and salinity, as well as its development over time in a spatially explicit manner. The model structure incorporates recent research within CSIRO Land and Water on relationships between vegetation type and water use (Zhang et al., 1999, 2001), the near-surface water balance (Dawes et al., 2002), the relationship and delay between changes in land use and in stream salinity (Gilfedder et al., 2002ab; Smitt et al., 2002) and the description of different groundwater flow systems (Coram et al., 2000).

A key constraint on the certainty of the predictions provided by this modelling approach is the small number of catchment scale studies undertaken that analyse the response of groundwater and stream salinity to land use changes. This recognition has motivated the construction of the BC2C model. A detailed description of the assumptions, simplifications and algorithms underlying the model is given in Dawes and Gilfedder (in review). Constant climate and land use were assumed in the present application. The output is generated on an annual time step and includes the water balance components and water and salt discharge for each delineated sub-catchment. In summary, modelling proceeds through the following steps:

1) A digital elevation model (DEM) is used to delineate sub-catchments of a desired approximate size.
For each grid cell, the water use is estimated based on land cover (i.e. forest or non-forest) from empirical relationships between annual rainfall and water use (Zhang et al., 1999; 2001).

The difference between rainfall and water use is partitioned between quick near-surface flow paths and water recharging the groundwater system.

The rate at which the groundwater system responds to land use is estimated from hydrogeological properties derived from the GFS framework (Coram et al., 2000).

For each runoff pathway (surface, near-surface and groundwater flow), annual water volumes entering the stream are multiplied with best estimate salt concentrations to calculate salt loads. These estimates were derived through review of regional data and workshops with local geohydrology experts (Dowling et al., in press).

The results from all grid cells are aggregated to yield sub-catchment and catchment totals.

The BC2C model has been calibrated and tested using measured stream flow and salinity time series in a number of smaller sub-catchments (Dawes et al., in review; Dowling et al., in press), some of which are located within the six catchments pre-selected for further analysis in this report. The model generally reproduced the observed trends well. BC2C has also been used at the scale of the entire Murray-Darling Basin to provide a spatial analysis of the expected stream flow and salinity impacts of afforestation, with input data in grids with a resolution of 0.25 to ~10 km, depending on the type of data (Dowling et al., in press; Table 2).

The BC2C model operates in a GIS environment and requires spatial data on mean annual rainfall, salt concentration in rainfall, tree cover and GFS. In the present study, we used the data described in Table 2 to model environmental responses 15 years after full afforestation. In principle the modelling results should not be used to determine the effect of partial afforestation, because the environmental response is not fully proportional to the area planted. However, a good first estimate can still be obtained this way.

Table 2. GIS input data used in the current application of the BC2C model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Underlying data</th>
<th>Grid cell size</th>
<th>Data source / reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital elevation model (DEM)</td>
<td>Surface elevation</td>
<td>~250 m (9&quot;)</td>
<td>AUSLIG (2000)</td>
</tr>
<tr>
<td>Annual rainfall</td>
<td>6000 stations, splined</td>
<td>2.5 km</td>
<td>BOM (1999)</td>
</tr>
<tr>
<td>Annual salt fall</td>
<td>24 stations, splined</td>
<td>1 km</td>
<td>CSIRO Land and Water (unpubl.)</td>
</tr>
<tr>
<td>Groundwater flow systems</td>
<td>Geological maps, DEM</td>
<td>Polygons based on 1:1 to 5 million maps</td>
<td>NLWRA/ CLW (Coram et al., 2001)</td>
</tr>
<tr>
<td>Forest cover</td>
<td>Landsat TM remote sensing data</td>
<td>25 m (250 m) *</td>
<td>MDBC (Ritman, 1995)</td>
</tr>
</tbody>
</table>

* Original land cover data at 25 m resolution was used to calculate percentage woody vegetation cover at 250 m resolution.
Each GFS is assigned best estimates for important geohydrological parameters, including the fraction of water draining from the soil that recharges the groundwater flow system, the salinity of discharged groundwater and the characteristic groundwater response time, defined as the period of time after half of the final effect is achieved. Values for the response time were based on expert opinion (see Dowling et al., in press) and are listed in Table 3.

Some of the catchments receive flow from upstream. These volumes are not included in the calculated stream flow, salt load and salinity values, and calculated values should not be taken to represent actual in-stream values at the catchment outlet.

### 2.3. Modelling potential forest productivity

We used a GIS coverage with potential forest productivity estimates produced by Booth et al. (in press) to assess which areas showed reasonable to good forest growth rates. To model forest productivity, the authors used PROMOD (Battaglia and Sands, 1997), a tree growth model that has been designed to accommodate the data available to forest managers and the outputs they require. The model uses mean climate data and an indicator of site fertility to estimate peak annual increment, which can be used as a measure of potential site productivity. Climate data used include mean monthly values of rainfall, number of rain days, daily maximum and minimum temperature, radiation, pan evaporation and vapour pressure deficit. A simple water balance calculation is used to model the effect of water limitations on growth. Other site factors required are the number of trees per hectare and soil characteristics. The soil is classified in a four-point system describing texture, stoniness, depth of soil, any features impeding root development and a measure of soil salinity.

Calibrating the model requires detailed information on canopy development. So far, PROMOD has been calibrated and tested for *Eucalyptus globulus*, *E. nitens* and *Pinus radiata* on sites in Tasmania and Western and South Australia (Sands et al., 2000; Booth et al., 2002). The model has also been used to predict site productivity over a 1 km grid (Mummery and Battaglia, 1999). There are tree species more suitable for low-to-medium

### Table 3. Expert’s best estimates of the response times of different groundwater flow systems (GFS). The values listed represent the number of years after land use change needed for 50% of the ultimate response to take place; the rate of response is also greatest at this stage.

<table>
<thead>
<tr>
<th>Description of Groundwater Flow System (GFS)</th>
<th>Response time (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0</td>
</tr>
<tr>
<td>Local aeolian sands</td>
<td>10</td>
</tr>
<tr>
<td>Local aeolian on regional alluvial</td>
<td>10</td>
</tr>
<tr>
<td>Local colluvial fans and granites</td>
<td>10</td>
</tr>
<tr>
<td>Local fractured basalts</td>
<td>20</td>
</tr>
<tr>
<td>Local fractured rock</td>
<td>20</td>
</tr>
<tr>
<td>Local upland alluvium</td>
<td>20</td>
</tr>
<tr>
<td>Intermediate and local fractured rock</td>
<td>150</td>
</tr>
<tr>
<td>Regional alluvial</td>
<td>1000</td>
</tr>
<tr>
<td>Regional limestone</td>
<td>1000</td>
</tr>
<tr>
<td>Regional marine under local Aeolian</td>
<td>1000</td>
</tr>
</tbody>
</table>
rainfall areas than these three, and the model will be calibrated for these in future. Booth et al. (in press) used the model calibrated for *Pinus radiata* to obtain a first indication of site productivity rates because, of the three species mentioned, it performs best in drier climates. The soil data used were extracted from a pre-release version of the Murray-Darling Basin Soil Information Strategy (MDBSIS, [www.brs.gov.au/mdbsis/](http://www.brs.gov.au/mdbsis/)). From the database, GIS layers with soil depth, texture, salinity, fertility, depth to groundwater and groundwater salinity were prepared at a resolution of 2.5 km (for the Murray Basin) to 10 km (Darling Basin). In each of these data categories, soils were assigned one to four points as required by PROMOD (see Booth et al., in press). Climate data were derived from the ESOCLIM prediction system (McMahon et al., 1996), which estimates climate variables on the basis of latitude, longitude and elevation. The latter was derived from the 9 second (~250 m) continental digital elevation model (DEM; Auslig, 2000).

We used the results of Booth et al. (in press) to assess which areas showed reasonable productivity rates. Based on expert opinion (T. Booth, CSIRO Forestry and Forest Products, pers. comm. 2003), we assumed these locations to be those areas for which a mean annual increment of >10 m³ ha⁻¹ y⁻¹ was modelled for *Pinus radiata*. Areas with predicted production rates of >15 m³ ha⁻¹ y⁻¹ were qualified as good productivity sites.
3. Results

3.1. Overall results

The outputs generated for the six catchments by the BC2C and PROMOD models are summarised in Table 4. A number of observations about these results were made with regard to the water budget, stream salinity and their change after afforestation. Firstly, both average annual water use and water yield tend to increase with annual rainfall. This follows directly from the model structure (see discussion). As a consequence, the absolute effect of land use change is greatest for catchments with higher rainfall. This general trend is somewhat moderated by the fact that the catchment level effect after afforestation on water yield also depends on the area that was not under forest already (cf. Table 1).

All catchments show moderately high estimated mean annual rates of salt mobilisation (34–71 t km⁻² y⁻¹) and mean annual stream salt concentrations (271–467 mg l⁻¹). The anticipated effect of afforestation on stream salt loads is a decrease of 5–18%, because higher water use leads to decreased groundwater recharge and, eventually, lower outflow of saline groundwater into streams. Stream salt concentrations are predicted to increase by 1.7–2.2 times after 15 years if the catchments were to be afforested entirely (Table 4).

Table 4. Current condition and expected changes 15 years after planting the non-forested area in the six pre-selected catchments, and estimated area suitable for afforestation with positive stream salinity changes after 15 years.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Bet Bet Creek</th>
<th>Southwest Goulburn</th>
<th>Upper Little River</th>
<th>Boorowa-Jugiong</th>
<th>Kyeamba-Tarcutta</th>
<th>Billabong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated mean annual water budget at present (before changes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall (mm y⁻¹)</td>
<td>580</td>
<td>688</td>
<td>715</td>
<td>720</td>
<td>839</td>
<td>680</td>
</tr>
<tr>
<td>Water use (mm y⁻¹)</td>
<td>477</td>
<td>546</td>
<td>614</td>
<td>569</td>
<td>653</td>
<td>542</td>
</tr>
<tr>
<td>Water yield (mm y⁻¹)</td>
<td>103</td>
<td>141</td>
<td>101</td>
<td>151</td>
<td>186</td>
<td>138</td>
</tr>
<tr>
<td>Estimated mean annual salt discharge at present (before changes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt load (t y⁻¹)</td>
<td>29,242</td>
<td>174,697</td>
<td>39,903</td>
<td>224,055</td>
<td>118,223</td>
<td>111,582</td>
</tr>
<tr>
<td>Salt generation (t km² y⁻¹)</td>
<td>45</td>
<td>47</td>
<td>34</td>
<td>71</td>
<td>51</td>
<td>37</td>
</tr>
<tr>
<td>Stream salinity (mg l⁻¹)</td>
<td>439</td>
<td>330</td>
<td>334</td>
<td>467</td>
<td>274</td>
<td>271</td>
</tr>
<tr>
<td>Expected changes 15 years after complete afforestation:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fraction of area not previously forested</td>
<td>73%</td>
<td>66%</td>
<td>56%</td>
<td>94%</td>
<td>66%</td>
<td>85%</td>
</tr>
<tr>
<td>Water yield (mm y⁻¹, %)</td>
<td>−58</td>
<td>−74</td>
<td>−52</td>
<td>−88</td>
<td>−86</td>
<td>−78</td>
</tr>
<tr>
<td>Salt generation (t km² y⁻¹)</td>
<td>−2</td>
<td>−6</td>
<td>−6</td>
<td>−8</td>
<td>−5</td>
<td>−5</td>
</tr>
<tr>
<td>Stream salinity (mg l⁻¹)</td>
<td>+956</td>
<td>+603</td>
<td>+559</td>
<td>+992</td>
<td>+545</td>
<td>+530</td>
</tr>
<tr>
<td>Available productive area resulting in a reduction in stream salinity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% area suitable *</td>
<td>0.0%</td>
<td>12.4%</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>% good productivity *</td>
<td>0.0%</td>
<td>12.1%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

* defined as areas for which Pinus radiata mean annual increment estimates of >10 (suitable) and >15 m³ ha⁻¹ y⁻¹ (good productivity) were obtained.
This is because the discharge of water at the catchment outlet is predicted to decrease more (46–57%) than the discharge of salt (5–18%) within this time frame.

In some or all of the catchments, stream salinity reduction may be achieved after a longer period of time or within certain parts of the catchment. We did not address this first possibility. We addressed the second issue by identifying areas within the six catchments for which the BC2C model predicts stream salinity reduction or no change 15 years after afforestation. We combined this with the PROMOD modelling results, to identify those areas that showed reasonable or good prospects for commercial forestry (i.e. a predicted mean annual increment for *Pinus radiata* of 10–15 or >15 m$^3$ ha$^{-1}$y$^{-1}$, respectively) as well as an expected decrease in stream salinity after 15 years. These results are listed in the bottom rows of Table 4. Only the Southwest Goulburn catchment showed significant areas where these conditions were met, amounting to an approximate 46,300 ha or 12% of the total area. The other five catchments combined showed only ~500 ha meeting above criteria. Further analyses therefore concentrated on the Southwest Goulburn catchment.

### 3.2. Results for the Southwest Goulburn catchment

Figure 2 shows the spatial distribution of some of the model inputs and predictions and, in Figure 2f, where reductions or no significant changes in stream salinity are expected within 15 years (the blue and grey areas in Figure 2f, respectively). The following observations were made:

- Much of the catchment has predicted *Pinus radiata* yields of >10 m$^3$ ha$^{-1}$ y$^{-1}$, with most of the ‘white’ area in Figure 2f representing areas that are already forested.

- After 15 years, increases in stream salinity are expected for some areas with local, and for all areas with intermediate to regional groundwater flow systems. Stream salinity decreases are expected in some of the local groundwater flow systems in colluvial fans and granites, and in aeolian or regional alluvial sediments (compare Figures 2c and f);

- The largest reductions in stream salinity can be expected where average annual rainfall is between ca. 650–850 mm y$^{-1}$ (compare the blue and grey areas in Figure 2f with 2a).
Figure 2. Model input and predictions for the Southwest Goulburn catchment.

Input layers shown (left column):
(a) Average annual rainfall isohyets (mm y\(^{-1}\); drawn by hand based on input data);
(b) The current fraction of woody vegetation cover; and
(c) the distribution of different groundwater flow systems (see Dowling et al., in press, for descriptions).

Output shown (right column):
(d) the change in water yield 15 years after afforestation (in mm y\(^{-1}\));
(e) change in salt discharge rates (in t km\(^{-2}\) y\(^{-1}\)) after 15 years;
(f) the change in the contribution to catchment discharge salinity, expressed as electrical conductivity (EC, µS cm\(^{-1}\) km\(^{-2}\)), but only for areas with less than 20% woody vegetation cover at present and Pinus radiata productivity estimates of >10 m\(^3\) ha\(^{-1}\) yr\(^{-1}\).
We estimated the change in mean annual water yield and stream flow EC if all 463 km² suitable for CEF were to be afforested. We repeated the exercise for the 10,000 and 20,000 ha with the highest predicted forest productivity, respectively. The results are summarised in Table 5. If all suitable areas were to be planted, after 15 years the reduction in water yield was estimated to be 64 GL y⁻¹ and the reduction in salt loads 21 kt y⁻¹. Because both amount to a reduction of ~12%, the impact on stream EC would be small, reducing it by <1 µS cm⁻¹.

It was observed earlier that water yield loss increases and salinity benefits decrease at higher rainfall. The expected changes in water yield and salinity after 15 years, expressed on an areal basis, do not change systematically if only the more productive areas are planted (Table 5). In all three cases, reductions in water yield, salt loads and salinity amount to respectively 130−138 ML, 44−46 t and 1.9−2.0×10⁻³ µS cm⁻¹ per year per km² planted. This lack of a trend suggests that the most productive areas are not necessarily located in areas of highest annual average rainfall.

Table 5. The anticipated impact on annual water yield and stream salinity at the outlet of the Southwest Goulburn catchment if forests were to be established on the entire area for which a reduction in stream salinity is expected after 15 years, or if only the most productive 200 or 100 km² were to be planted, respectively. Numbers are aggregated to catchment level as well as divided by the area planted for comparison (note: total values do not equal in-stream values at the catchment outlet because the Southwest Goulburn area receives flow from upstream).

<table>
<thead>
<tr>
<th>Effects 15 years after afforestation of Entire area</th>
<th>Most productive 200 km²</th>
<th>Most productive 100 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in average annual water yield in ML yr⁻¹</td>
<td>−63,952</td>
<td>−27,349</td>
</tr>
<tr>
<td>in mm y⁻¹ (=ML km⁻² yr⁻¹)</td>
<td>−138</td>
<td>−138</td>
</tr>
<tr>
<td>Change in mean annual salt discharge in t y⁻¹</td>
<td>−21,391</td>
<td>−9,161</td>
</tr>
<tr>
<td>in t km⁻² y⁻¹</td>
<td>−46</td>
<td>−46</td>
</tr>
<tr>
<td>Change in mean annual EC for catchment in µS cm⁻¹</td>
<td>−0.90</td>
<td>−0.40</td>
</tr>
<tr>
<td>in µS cm⁻¹ km⁻²</td>
<td>−0.00195</td>
<td>−0.00201</td>
</tr>
</tbody>
</table>
4. Discussion

4.1. Change in water yield

The model prediction that the absolute change in both annual water use and water yield increase with annual rainfall follows directly from the structure of the BC2C model. The model uses a simple but well-established empirical relationship that states that for the same cover type water use increases progressively slower as rainfall increases (Zhang et al., 1999, 2001). This relationship is moderated by the amount of woody vegetation, which uses more water than shorter vegetation types (Figure 2). Based on the ‘Zhang curves’, annual water yield losses after afforestation can be expected to increase roughly from <100 mm (or <100 ML km\(^{-2}\)) where rainfall is <400 mm, to ~150 mm (or ~150 ML km\(^{-2}\)) where rainfall is 600 mm and more beyond that (see also Vertessy et al., 2003).

The Zhang curves used in the BC2C model reflect the water use of mature forests. Patterns in water use over time, including the lower water use immediately after planting and the higher water use during the rapid growth phase of plantations, are not explicitly accounted for. Depending on species an rotation length, forest water use 15 years after establishment may differ considerably from the curve-based value and therefore have a different effect on water yield than predicted (Table 4). Future development of our capacity to predict the environmental impacts of CEF forestry will address this.

Figure 3. Relationship between land cover type and mean annual rainfall and water use (evapotranspiration). The dotted lines show the empirical relationships found by Zhang et al. (1999, 2001) in an analysis of global stream flow data, the solid line a similar relationship developed by Holmes and Sinclair (1986) for local catchments mainly in Victoria, Australia (see Vertessy et al., 2003 for more details). Note that the two approximations diverge at the lower and higher ends of the rainfall range.
4.2. Change in stream salt loads and salinity

Using the model results, we anticipated a modest decrease (5−18%) of stream salt loads 15 years after afforestation for all catchments (Table 4). This is because the higher forest water use leads to decreased groundwater recharge and, eventually, lower outflow of saline groundwater into streams. Again for all catchments, average salt concentration in the stream was about doubled after 15 years, because the reduction in total water yield still surpassed the reduction in groundwater outflow at this stage. The reduction of groundwater outflow is a slow process that depends on the size and responsiveness of the groundwater flow system (Dawes et al., 2004). Afforestation can also reduce the amount of water flowing through the stream through quicker, less saline systems such as overland flow and lateral flow through the soil. When this reduction occurs before the reduction in groundwater flow, the short-term consequence will be that the out-flowing groundwater becomes less diluted and stream salt concentration first increases before finally decreasing to a lower value than before afforestation. At whole catchment level, the model predicts this process to take more than 15 years in all cases.

4.3. Physical constraints to CEF

Opportunities for achieving stream salinity reductions within 15 years appeared to be limited in the six pre-selected catchments. For the Southwest Goulburn catchment only 12% of the area would produce a reduction in stream salinity after afforestation. Within this catchment, the main constraints to CEF were the response time of the groundwater flow system, and the relative magnitude of reductions in stream flow and in stream salt loads.

The greatest impacts were predicted for local flow systems in aeolian deposits and in colluvial fans and granites. This is readily explained by the parameters assigned to the GFS classes: these systems are expected to respond within 10 years, whereas slower responses (>20 years) are assumed for all other GFSs (Table 3; Coram et al., 2000). Because the response times used for modelling are initial estimates, the difference between assumed and actual GFS response rate creates an important uncertainty in our analysis.

The reduction in stream salinity did not increase with annual rainfall. At annual rainfall depths beyond ~850 mm y\(^{-1}\), the decrease in water yield after afforestation dominated the reduction in salt generation. Most of the suitable area within the Southwest Goulburn experienced annual rainfall of more than about 650 mm. It appears that most fast responding GFSs coincide with higher rainfall zones (compare Figure 2a and 2e). Also it is likely that groundwater salt concentration increases with decreasing mean annual rainfall. Future analyses will clarify this.

The preliminary productivity analysis suggested that forest growth rates per se do not necessarily have to be the main constraint to CEF systems. Although subject to a number of simplifications and assumptions, commercial production rates appear to be achievable in almost the entire Southwest Goulburn catchment area.
5. Conclusions

5.1. CEF opportunities in the six pre-selected catchments

Combined, the results of biophysical and productivity modelling suggested that CEF benefits appear to be achievable in limited areas. The present, preliminary study suggests that the Southwest Goulburn catchment has substantial areas within its perimeter with CEF opportunities. The other catchments may have less of such areas. The main constraints to achieving environmentally beneficial impacts of afforestation can be summarised as:

- A change from short, shallow rooted vegetation types such as pasture or crops to plantation forest will always lead to a decrease in water yield. The magnitude of this decrease is roughly commensurate with the area planted and the amount of rainfall in this area, although moderated by other factors (e.g. stand management). Therefore, water yield losses are minimised in low rainfall areas, but here productivity is likely to become the main constraint.

- The response of stream salinity to afforestation and the rate at which this occurs depends strongly on the type of groundwater system. The most rapid and largest impacts on stream salt concentrations can be expected in local groundwater systems which typically are found in (often wetter) upland areas (Dawes et al., in review). The greatest stream salinity problems are typically experienced in drier areas.

Opportunities for CEF can be expected where the – often opposing – constraints outlined above can be reconciled. The proposed CEF framework will serve to find this balance.

5.2. Main uncertainties and needs for development

The current study provides only a preliminary assessment intended to select a suitable focus catchment for further development of the CEF concept and modelling framework. Our analysis demonstrates a number of weaknesses in the modelling approach that will need improvement in future. Each of these weaknesses relate to the way in which the assessments of environmental benefits and productivity estimates are derived and should be compared.

The most important uncertainties in estimating the environmental impacts of afforestation relate to the sub-surface groundwater flow system. The hidden nature, often slow response and diversity in groundwater flow systems have limited the collection of data and understanding of groundwater behaviour, and therefore also stream salinity response after land use change. The BC2C model represents the current state of knowledge and its predictions are generally in good agreement with field observations, but the uncertainties associated with the model and the estimated GFS response times are considerable. Future research in the CEF project will pursue this problem in a number of ways.

- We will engage local stakeholders and expertise to ensure that the available local information is optimally used in modelling. This should improve the accuracy of the predictions.
– We will continue to use stream flow and salinity time series at gauging stations within the Southwest Goulburn catchment to validate model predictions. We will also use information from detailed micro-catchment studies to help in refining the model where necessary.

– At valley level GFS response rate is confounded by variations in climate and topography. We aim to use some of the more recently available data sets and techniques, such as combining digital terrain analyses with geology, soil and landscape mapping to infer the occurrence and density of perennial streams and possible links between GFSs and streams.

The type of model development outlined above is expected to provide more realistic predictions but cannot substitute for the need for more ‘on-ground’ experimental work to better understand the geohydrological processes leading to salinity.

In terms of the suitability for forestry, the productivity estimates that were produced should be seen as a first indication only. The simulated Pinus radiata is unlikely to be the best option for forestry in low-to-medium rainfall areas. Future CEF research will be addressing other, more suitable species and will calibrate the PROMOD model for these species. There are also important direct links between tree or site productivity and environmental impacts. Three examples are:

- There is an almost direct relation between tree growth and water use that is not fully accounted for in the current modelling exercise. One particular tree species may be more productive than another because it has a deeper root system and uses more water. This will therefore also change its environmental impacts, whether for good or bad.

- The timing of forestry operations such as thinning or logging, and spatial characteristics such as stocking density also affect water use and will need to be taken into account. For example, the current modelling exercise did not account for the effect of stand age on forest water use (e.g. Vertessy et al., 2003).

- There may be links between the suitability of a certain soil type for forestry and the hydrological properties of the soil and groundwater system below. This may include the partitioning of excess rainfall into quick near-surface flow pathways and groundwater recharge, and how this partitioning changes after afforestation.

These various links will be addressed as the CEF project proceeds. Future efforts will use a tree productivity model (3PG, Landsberg and Waring, 1997) that includes an explicit representation of the physical processes determining the trade-off between forest growth rate and water use, as well as the transfer of water through the soil. Linking these model components with the groundwater system may allow some of the issues above to be accounted for.

The current study does not provide an economic framework for balancing the environmental and commercial benefits of CEF. The response of stream flow and salt loads after afforestation changes over time and a time horizon will need to be set when evaluating either the average or the final impacts over a number of years. The time horizon chosen will need to be long enough to achieve significant environmental benefits, but short enough to influence economic decisions. Also, where stream flow and salinity have not yet reached new equilibrium, the environmental benefits of afforestation should be compared to a non-intervention scenario rather than the status quo.
Acknowledgements

This work was funded through the Strategic Plan for National Investment under the Natural Heritage Trust.

CSIRO Forestry and Forest Products kindly supplied forest productivity estimates. Darryl Mummery performed the grid-based PROMOD model runs and Tom Jovanovic supplied the data for the selected catchments. The productivity modelling was funded by the Joint Venture Agroforestry Project (JVAP).

We thank Brendan Moran, Nico Marcar, Trevor Booth, Phil Polglase and Mat Gilfedder for their helpful comments on an earlier draft.
References


## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUSLIG</td>
<td>Australian Surveying and Land Information Group (Commonwealth Department of Administrative Services)</td>
</tr>
<tr>
<td>BC2C</td>
<td>Biophysical Capacity to Change model (Dawes et al., in review)</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology</td>
</tr>
<tr>
<td>BRS</td>
<td>Bureau of Rural Sciences</td>
</tr>
<tr>
<td>BSMS</td>
<td>Basin Salinity Management Strategy</td>
</tr>
<tr>
<td>CEF</td>
<td>Commercial Environmental Forestry</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity (a measure of salt concentration)</td>
</tr>
<tr>
<td>GFS</td>
<td>Groundwater Flow System (Coram et al., 2000)</td>
</tr>
<tr>
<td>MDB</td>
<td>Murray-Darling Basin</td>
</tr>
<tr>
<td>MDBSIS</td>
<td>Murray-Darling Basin Soil Information System</td>
</tr>
<tr>
<td>NAP</td>
<td>National Action Plan (for Salinity and Water Quality)</td>
</tr>
<tr>
<td>NLWRA</td>
<td>National Land and Water Resources Audit</td>
</tr>
<tr>
<td>PROMOD</td>
<td>Productivity Model (Battaglia and Sands, 1997)</td>
</tr>
<tr>
<td>SPIF</td>
<td>Scenario Planning Investment Framework</td>
</tr>
</tbody>
</table>