CSIRO Land and Water

Representing plantation scenarios in hydrological modelling:

Requirements and limitations in representing Commercial Environmental Forestry scenarios in stream flow and salinity modelling

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

Commercial Environmental Forestry report CLW/02

CSIRO Land and Water Client Report
March 2004

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Executive Summary

Returning forest cover to decrease groundwater recharge has the potential of reversing some of Australia's stream salinisation problems. Plantation forests in low-to-medium rainfall areas (400-800 mm y^{-1}) are currently not widespread and, at the lower end of this range, typically commercially marginal or unprofitable. However, their 'salinity benefits' may provide an incentive for expansion. The Commercial Environmental Forestry (CEF) project was jointly initiated by DAFF and CSIRO to develop forestry systems for profitability, environmental benefits and regional community development in those low-to-medium rainfall zones. The project will develop a Scenario Planning Investment Framework (SPIF) that integrates knowledge and models of the catchment water and salt balance, forest productivity and forestry economics. It will enable stakeholders (governments, catchment management authorities, forestry industry and private investors) to assess potential plantation benefits and decrease uncertainty and risk in decision-making. The Southwest Goulburn catchment has been selected as the CEF project focus area. Hydrological modelling suggested that ~450 km^2 or 12% of the catchment has potential for realising salinity benefits through afforestation (Van Dijk *et al*., 2004).

The overall aim of this report is to assess how different plantation expansion scenarios can be defined in a form suitable as input for modelling stream salinity and stream flow impacts. Specific aims are to (1) identify the data requirements of the current hydrological model; (2) investigate the plantation characteristics that can be represented in hydrological modelling at present or in the near future; (3) identify the factors determining the potential area suitable for CEF and investigate the spatial correlation between these factors. The conclusions drawn with respect to these three aims can be summarised as follows:

(1) The hydrological model used so far (BC2C, Dawes and Gilfedder, in review) uses generalised empirical relationships between rainfall and potential and actual evaporation that distinguish only between either forest or non-forest cover (Zhang *et al*., 1999; 2001). Scenarios thus only need to define forested and non-forested areas.

(2) The Zhang model does not describe the influence of forest characteristics and management (species composition, productivity, age, thinning and stocking density) on water use. Future work linking forest growth and hydrological models will allow the most important characteristics to be represented.

(3) The area identified as potentially suitable for CEF in earlier modelling exercises based on salinity benefits and productivity estimates, will be reduced by the fact that not all land will be available for private forestry investment and by economic considerations. Other environmental impacts (e.g. on stream flow quantity, biodiversity and carbon sequestration) can positively or negatively contribute to the suitability of an area for new CEF plantations. Future work in developing the SPIF will address this by including additional GIS-based information and benefit valuation. Analysis of biophysical model results showed that a forest expansion strategy targeted to maximise stream salinity reductions achieved after 15 years can substantially improve the end-of-valley benefits of plantation expansion, apparently without having markedly different consequences for water yield or production. Plantings targeted to minimise water yield loss or maximise production appear less effective. The impact of these strategies on salinity benefits is confounded by the complex spatial distribution of rainfall and groundwater flow systems. Additional targeting strategies may be included as scenarios in future, for example minimising transport costs or maximising other environmental benefits or using a different time scale.

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Abbreviations

BC2C	Biophysical Capacity to Change model (Dawes *et al*., in review)
CEF	Commercial Environmental Forestry
DAFF	Department of Agriculture, Forestry and Fisheries
DEM	Digital Elevation Model
EC	Electrical Conductivity (a measure of salt concentration)
GIS	Geographical Information System
GFS	Groundwater Flow System (Coram *et al*., 2000)
RMSE	Root Mean-Square Error
SPIF	Scenario Planning Investment Framework
LAI	Leaf Area Index

1. Introduction

1.1. Background

Australia is facing severe salinity problems. Clearing of native vegetation has led to increased recharge of groundwater systems in many areas, mobilising salt that is now degrading land and water resources. Returning deeper rooted and more permanent vegetative cover will decrease groundwater recharge and so can mitigate this process, although the response time can be long.

To combat stream salinisation, the Murray Darling Basin Commission aims to establish 1.5 million hectares of targeted woody vegetation by the year 2050 for a projected cost of $17 billion. The Murray Darling Basin Salinity Management Strategy proposes farm forestry for revegetation in low-to-medium rainfall areas (400-800 mm y^{-1}). Parallel to this, the ‘Plantations 2020 Vision’ was initiated jointly by governments and the forestry industry in 1997 (DPIE, 1997). It aims to enhance regional wealth creation and international competitiveness by trebling the area of commercial tree crops by 2020 and is on track to achieving this expansion.

Despite these seemingly complimentary goals, traditional forestry investments have made little progress in extending forestry into lower rainfall areas (A. Gerrand, Bureau of Rural Sciences, Canberra, pers. comm., 2004), due to low productivity, marginal profitability, lack of established transport and processing infrastructure and a reluctance to diversify from traditional farming enterprises. The off-farm private investors (industry and financial sectors) needed to underpin profitable forestry require sound information to indicate that such investment would be commercially viable.

Forestry may become commercially viable in some of these areas if environmental benefits can be taken into account. In addition to traditional wood products, potential benefits of ‘commercial environmental forestry’ (CEF) include decreased land salinity, carbon sequestration, soil conservation and rehabilitation, reduced stream nutrient and sediment loads, and enhanced landscape diversity, ecological connectivity and biodiversity. There will also be economic and social benefits for rural communities (Alexandra, 2002).

1.2. Project description

The Commercial Environmental Forestry (CEF) project was initiated by the Commonwealth Department of Agriculture, Fisheries and Forestry (DAFF) and CSIRO through the Natural Heritage Trust program. The project aims to develop commercially viable and environmentally beneficial farm forestry systems in low-to-medium rainfall zones typical for much of Australia. Specific aims are to quantify the environmental benefits of plantations; improve predictions of plantation productivity; and increase financial returns for growers, processors and investors in farm forestry.

The project will assimilate knowledge from various scientific disciplines via a Scenario Planning Investment Framework (SPIF) that will integrate models of catchment water and salt dynamics, forest growth and forest economics (including market size, product value and transport costs). The SPIF will enable a range of stakeholders (governments, catchment management authorities, forestry industry and private investors) to assess the impacts of various economic factors on potential plantation benefits and will decrease uncertainty and risk in decision-making.

The SPIF framework is being developed and tested in a focus area where CEF is most likely to be viable. Six potentially suitable focus catchments in New South Wales and Victoria were compared based on the following selection criteria (Van Dijk *et al*., 2004):

- Located within the 400-800 mm rainfall range;
- Draining into the Murray-Darling system;
- Area coinciding with one or more well defined sub-catchments;
- Reduced stream salinity can be expected rapidly enough to be taken into account in economic analysis (tentatively defined as 15 years);
- Local knowledge and data on soils, GFSs and stream flow and water quality in the catchment and in sub-catchments;
- Expected forest production rates are sufficient to suggest commercial potential (tentatively based on predicted production rates for pine; Booth *et al*., in press).

For each catchment, the likely changes after 15 years in catchment stream flow and salinity, per unit area of plantation established on non-forested land, were estimated using the Biophysical Capacity to Change (BC2C) model (Dawes and Gilfedder, in review). Areas with commercial forest production potential were identified using modelling results of Booth *et al*. (in press). Of the six catchments, the Southwest Goulburn suggested the greatest potential for CEF with 453 km² or 12% of the catchment apparently suitable.

The SPIF being developed for the Southwest Goulburn will initially integrate spatial data on predicted forest productivity, stream flow and salinity impacts and transport costs. Its first application will provide a first approximation of the economics of various scenarios. If CEF opportunities can indeed be demonstrated to be likely, this trial will identify key data and knowledge gaps to guide work for subsequent years.

1.3. Aim and structure of this report

Hydrological modelling will form an integral part of the SPIF. A wide variety of forestry development scenarios can be conceived to test the SPIF, both in terms of plantation characteristics and the size and spatial distribution of plantations. Each of these scenarios might lead to different hydrological outcomes at the catchment level. Plantation characteristics and management, such as species, stocking density, rotation length and whether there is replanting after harvest, can affect water use. Water use will affect stream water yields and groundwater recharge, and through this the discharge of saline groundwater into streams and ultimately stream salt concentrations. Hydrological impacts vary spatially and therefore the area and distribution of new plantations affect catchment level outcomes.

This report examines our existing ability to model the impacts of afforestation on stream flow and salinity and addresses the following questions:

(1) What are the **current input requirements for the hydrological model** (Section 2)?

(2) What are the limitations for **representing plantation characteristics and management** in the current hydrological modelling approach and how can these limitations be addressed (Section 3)?

(3) Which physical and socio-economic factors affect the potential area suitable and available for CEF, and to what extent do different **targeted forest expansion scenarios** in the Southwest Goulburn catchment influence catchment level outcomes (Section 4)?

In Section 5 conclusions are drawn and challenges and opportunities for improving the way plantation scenarios are represented in hydrological modelling are identified.

This report provides technical background to guide consultation between the stakeholders and technical experts who will ultimately define realistic plantation scenarios for the Southwest Goulburn catchment.

2. Hydrological model input requirements

2.1. Structure of the BC2C model

The Biophysical Capacity to Change (BC2C) model (Dawes *et al*., 2004; Dawes and Gilfedder, in review) has been developed to predict the spatial and temporal impacts of land use change on stream flow and salinity. The model structure incorporates relationships between vegetation type and water use; the influence of vegetation type on the near-surface water balance; and the spatial and temporal relationships between changes in land use and changes in stream salinity for specific types of groundwater flow system.

The small number of catchment scale studies describing the response of groundwater and stream salinity to land use changes and the large variation in responses of different groundwater flow systems to revegetation motivated 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). The model can operate in a GIS environment and requires spatial data on mean annual rainfall, rainfall salinity, tree cover and groundwater flow systems (GFSs; Coram *et al*., 2000). 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.
2) For each grid cell, water use (the sum of all evapotranspiration components) is estimated based on land cover (forest or non-forest/pasture) from generalised empirical relationships between long-term annual rainfall and water use.
3) The difference between rainfall and water use is partitioned between quick near-surface flow paths and water recharging the groundwater system.
4) The rate at which the groundwater system responds to land use change is estimated from hydrogeological properties derived from the GFS classification framework.
5) For each runoff pathway (surface, near-surface and groundwater flow), annual water volumes entering the stream are multiplied by best estimates of salt concentrations to calculate salt loads. These estimates are derived through review of regional data and workshops with local geohydrology experts.
6) 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). The model generally reproduced the observed trends well although the actual numbers did not always agree, primarily due to the strong spatial heterogeneity in GFS characteristics. 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 1. GIS input data used in applying the BC2C model to aid selection of a focus research area (for more information on input data see Van Dijk *et al.*, 2004).

Layer	Underlying data	Grid cell size
Digital elevation model (DEM)	Surface elevation	~250 m
Annual rainfall	6000 stations, splined	2.5 km
Annual salt fall	24 stations, splined	1 km
Groundwater flow systems	Geological maps, DEM	Polygons based on 1:1 to 5 million maps
Forest cover	Landsat TM remote sensing data	25 m (250 m) *

* Original land cover data at 25 m resolution was used to calculate percentage woody vegetation cover

2.2. Previous model application within the CEF project

The BC2C model was used in the initial stages of the CEF project to help select the Southwest Goulburn catchment as a focus research area (Van Dijk *et al.*, 2004). Based on the criteria mentioned in the introduction, the hydrological impacts of afforestation were modelled for six pre-selected catchments and combined with forest productivity estimates (Booth *et al*. in press). The input data used are summarised in Table 1. Additional input data are the geohydrological parameters describing different GFSs, including the fraction of water draining from the soil to the groundwater flow system, the salinity of discharged groundwater and the characteristic groundwater response time.

The environmental responses 15 years after full afforestation of the available (i.e. not yet forested) area were modelled. This does not mean that the results are only relevant for this scenario: because the results were expressed as change per hectare of plantation established, they give an indication of the effect of partial catchment afforestation. The 15 year time-frame was chosen as a period suitable for economic analyses.

A GIS coverage with potential forest productivity estimates produced by Booth *et al*. (in press) was used to assess which areas showed reasonable to good forest growth rates. It was assumed that reasonable productivity coincided with a mean annual increment of >10 m^3 ha^{-1} y^{-1} modelled for *Pinus radiata*, whereas predicted production rates of >15 m^3 ha^{-1} y^{-1} were qualified as good.

The modelling results for the six pre-selected catchments indicated that important CEF opportunities were only to be expected in the Southwest Goulburn catchment and this contributed to its selection as the focus research area. The spatial distribution of water yield loss and salinity change for the catchment is shown in Figure 1a and b, respectively. It should be noted that the Southwest Goulburn catchment receives flow from upstream. These volumes are not included in the calculated stream flow and salinity values, and calculated values should not be taken to represent actual in-stream values at the catchment outlet. This difference will be taken into account in future modelling exercises.

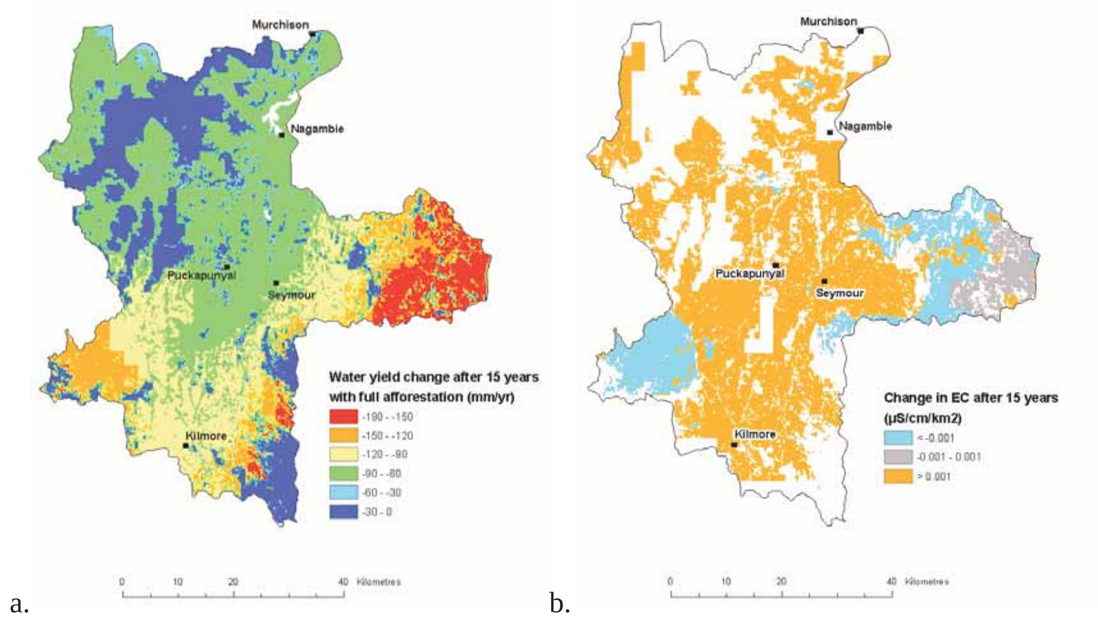

Figure 1 Hydrological modelling results for the Southwest Goulburn catchment. Shown are the predicted changes 15 years after afforestation in (a) water yield (in mm y^{-1}) and (b) the contribution to catchment discharge salinity, expressed as electrical conductivity (EC, $\mu S\ cm^{-1}\ km^{-2}$), but only for areas with less than 20% woody vegetation cover at present and *Pinus radiata* productivity estimates of >10 $m^3\ ha^{-1}\ yr^{-1}$ (source: Van Dijk *et al.*, 2004).

2.3. Water use model component

The BC2C model estimates evapotranspiration using a simple but well-established empirical relationship that states that water use increases with rainfall (Zhang *et al*., 1999, 2001; Figure 2). The parameters describing these 'Zhang curves' were based on an analysis of over 250 paired-catchment and single-catchment water balance studies world-wide (Zhang *et al*., 1999, 2001). Catchment size varied between <1 km^2 and 6×10^6 km^2. Steep catchments, catchments with shallow soils (<2 m) and catchments with substantial snowfall were excluded from analysis. Subsequently, catchment land cover was classified as either grassland, forested (>70% forest cover) or mixed. Separate curves were fitted to the measured catchment rainfall and inferred water use data (i.e. rainfall minus catchment runoff). Because of the limited sample size, no separate analysis was made between plantation and natural forests or between forests of different age, composition or management.

As a consequence, the resulting equations describe water use as a function only of broad vegetation type (forest or grassland), mean annual rainfall and potential evapotranspiration, occurring when water availability is unlimited and estimated using the Priestley-Taylor equation (Zhang *et al*., 1999, 2001). Hydrological modelling therefore requires no more than a GIS layer that assigns to each pixel either non-forest (taken to be synonymous to 'grassland') or forest cover.

3. Representation of forest characteristics and scope for improvement

3.1. Introduction

The catchment studies on which the ‘Zhang curves’ were based represent a wide variety of forest types, ages and management as well as physical catchment attributes and climate (from boreal to humid tropical to semi-arid). In this respect the agreement between estimated and measured water use is encouraging (Figure 2a). The variation in annual water use left unexplained (the root mean-square error, RMSE) was 93 mm for forests. Although the Zhang curves have proven robust and useful in many applications, the generalisation across forest and catchment types places limits on how well the effect of plantation characteristics on hydrological processes can be described. For 800 mm annual rainfall, the Zhang curves predict a difference in annual water use between forest and non-forest cover of ~200 mm, decreasing to almost zero at 400 mm annual rainfall (Figure 2a). The uncertainty of estimate is substantial compared to these values: although the scatter seems to decrease towards lower rainfall,Figure 2a and b also suggest that the Zhang curves may actually overestimate forest water use and underestimate grassland water use

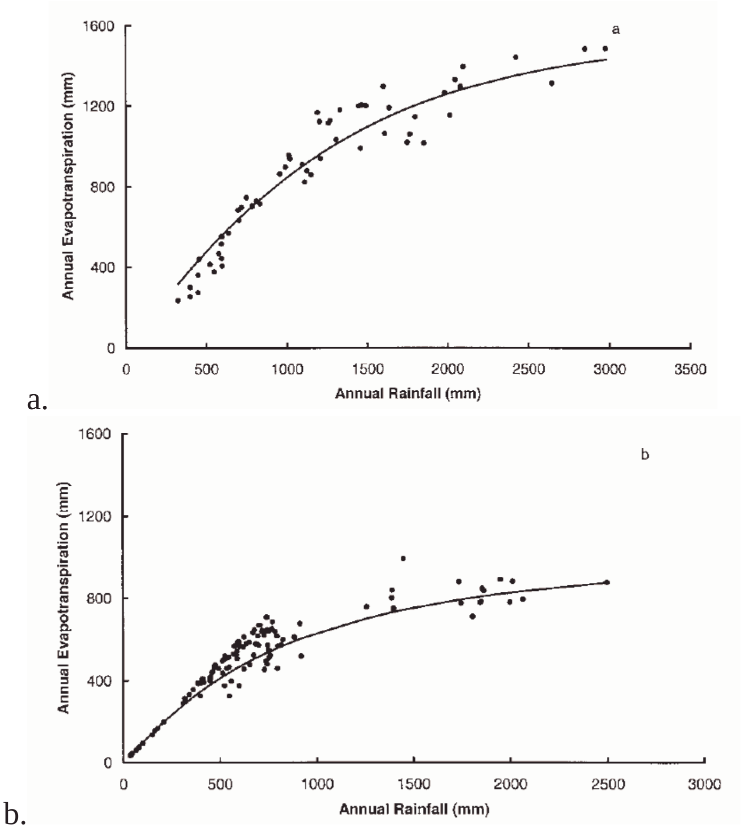

Figure 2. Scatter plots showing the data from catchment studies and the curves based on them for (a) forested catchments and (b) grassland catchments (source: Zhang *et al.*, 2001).

in this rainfall regime, i.e. the difference between the two may actually be less.

In the next section, a number of potentially relevant forest characteristics are discussed in terms of the consequences of this simplified approach for prediction accuracy and the scope for improvement.

3.2. Forest type and species

So far, three eucalypt species (*Eucalyptus cladocalyx*, *Corymbia maculata* and *Eucalyptus occidentalis*) have been identified as potentially suitable species for CEF and may be included in the SPIF in alternative scenarios (T. Booth, CSIRO Forestry and Forest Products, pers. comm., 2004). Additional scenarios likely to be included are afforestation with ‘generic’ pine and eucalypt plantations, respectively. Water use differences between these scenarios are currently not predicted by the BC2C model but in reality might exist.

The forested catchments in the analysis of Zhang *et al*. (2001) include comparable numbers of natural and plantation forests and a wide variety of species. Depending on forest composition, structure and plantation rotation length, differences in mean water use by natural and plantation forests may exist. In low rainfall climates and in the absence of other water sources (e.g. shallow groundwater), however, both growth rate and water use will become limited by water availability and the water use of plantation and natural forests are likely to converge. There is some scope to perform analysis on the collected catchment data separately for plantation and natural forests, although this will decrease the sample size and therefore the statistical significance of the results (L. Zhang, CSIRO Land and Water, pers. comm., 2004). A promising technique in this respect is meta-analysis, which is able to make optimum use of differences in experimental conditions among the data (Arnqvist and Wooster, 1995). The number of studies is too small to use this same approach to separate the effects of species and management from whether the forest is natural or planted, however.

Several studies on water use by pine and eucalypt plantations, and to a lesser extent natural eucalypt forests, have been undertaken in Australia. These provide somewhat conflicting evidence on differences in water use. Contrary to observations made in countries like South Africa and India, there are indications that pine plantations in Australia tend to use more water than eucalypt forests (Vertessy, 2001). Most Australian studies compared pine to natural rather than planted eucalypts, which may explain much of this discrepancy. In addition, the differing ecological environment (insect predation, pests and diseases) may make pine growth more and eucalypt growth less prolific than elsewhere. A model-aided analysis of runoff from 28 sub-catchments in the Murrumbidgee catchment by Vertessy and Bessard (1999) suggested that for a mean annual rainfall of <600 mm, any closed forest (pine or eucalypt, natural or planted) is likely to use virtually all available rainfall.

A (pseudo) paired catchment experiment in New South Wales (755 mm annual rainfall) showed an almost 200 mm runoff increase for the year following full conversion from natural dry sclerophyll forest to radiata pine (*Pinus radiata*). This changed to a relative runoff decrease of ~50 mm y^{-1} after 10 years and a return to close to original stream flow conditions after 16 years (Putuhena and Cordery, 2000). The partitioning of water use between rainfall interception losses, soil evaporation and tree transpiration was still very different from the original forest at this time, however. In a long-term paired catchment study in northeast Victoria, radiata pine also used less water for the first 10 years after establishment were compared to a natural dry sclerophyll eucalypt forest (Bren and

Hopmans, 2000). The two forests subsequently showed little difference in water use until the plantation was thinned, resulting in a slight increase in stream flow. In Southeast South Australia, under comparable soil and climatic conditions, radiata pine and Tasmanian blue gum (*Eucalyptus globulus*) use similar amounts of water, although rainfall interception by the pines is greater.

Water use studies for the three potentially suitable CEF species mentioned are few or none. Benyon *et al*. (1999, 2001) compared water use by a number of eucalypts including *E. cladocalyx* and *E. occidentalis*. Tree water use differed between species, but expressed on a per unit leaf area basis the difference was not significant in most cases. The few significant differences in leaf water use were attributed to differences in root architecture that affected access to soil water and groundwater. Hatton *et al*. (1998) also observed conservancy in leaf water use for a variety of eucalypt species. Opportunities to include the relationship between eucalypt water use and leaf area (expressed per unit area as leaf area index, LAI) exist through establishing a link with the forest growth model (3PG, Landsberg and Waring, 1997) used within the SPIF.

3.3. Forest age, productivity and management

The Zhang curves used in the BC2C model reflect the water use of forests of various ages. Depending on species and rotation length, forest water use at different stages after establishment may differ considerably from the curve-based value. For example, water use by South-eastern Australian mountain ash (*Eucalyptus regnans*) forest, re-established after clear-felling or burning, is lowest during the first 4-6 years, but subsequently increases to reach a maximum after about three decades before slowly returning to pre-disturbance levels over the next 50 or more years (Kuczera, 1987; Vertessy *et al*., 1998, 2003). Age-related variation in water use will also occur in low-to-medium rainfall plantations, mainly due to lower water use prior to canopy closure. Therefore the length of rotation will have an effect on (mean) forest water use. The mean water use over a full rotation depends, among others, on the rate of canopy closure and the length of the rotation, which can both differ between species. Plantation grown eucalypts generally close canopy faster (3-4 years) than radiata pine (6-8 years). In Southern Australia, most blue gum is currently grown on a 10-12 year rotation, compared to 27-35 years for radiata pine (R.G. Benyon, CSIRO Forestry and Forest Products, pers. comm., 2004).

Because of the physiological link between carbon assimilation and transpiration, more biomass producing plantation forests are likely to use more water under otherwise equal conditions. For example, a certain tree species may be more productive because it has a deeper root system and greater access to subsurface water. Differences in productivity will be reflected in differences in LAI (Hatton *et al*., 1998). High biomass production does not equate to high wood production however (Theiveyanathan *et al*., 2000). Careful soil and stand management and genotype selection can improve wood production without increasing water use (e.g. Olbrich *et al*., 1993).

Thinning operations can either decrease water use, due to the reduced number of trees, or increase it because of temporarily invigorated growth of the remaining trees or regrowth from stumps (Swank *et al*., 1988; Hornbeck *et al*., 1993). The net effect of these opposite processes will be reflected in LAI and depends on initial planting density, thinning intensity, the rate of leaf area recovery and the increase of evapotranspiration from the understorey and soil (Black *et al*., 1980; White *et al*., 2001). The earlier mentioned slight stream flow increase after thinning the Victorian pine plantation presumably reflected decreased water use (Bren and Hopmans 2000). Certainly, in low rainfall environments a temporary decrease of total water use after thinning is most likely. Thinning trials in eucalypt plantations within the Goulburn-Broken catchment (Benalla) and in South Australia showed increased groundwater recharge for little more than one year, after which water use appeared to return to its former level.

There is no strong evidence to suggest an important effect of initial forest stocking density on water use within the range of stocking rates common in commercial forestry. Experimental evidence suggests that Australian eucalypt forests attain a leaf area that is in equilibrium with water availability (which may include groundwater in addition to rainfall) rather than being controlled by stocking density (Hatton *et al*., 1998; White *et al*., 2000). Stirzaker *et al*. (1999) modelled the water use of trees planted on pasture at low densities or in belts. Their results suggest that this increases the water use of individual trees if these have access to groundwater. Overall system water use was still intermediate between that of pasture and a closed forest however.

Summarising, re-analysis of the catchment studies collected by Zhang *et al*. (2001) is unlikely to be able to provide information on the effect of forest age, productivity or management on (relative) water use. However, including links between LAI (and perhaps water use) predictions from the forest growth model and the water use component of the BC2C model can assist to include these effects in hydrological modelling.

3.4. Water use of non-forest land cover

Because the hydrological effect of afforestation depends on the difference between pre-forest and forest water use, accuracy in both estimates is of equal importance. The Zhang curve for non-forest land uses was originally based on data for catchments under grassland (Zhang *et al*., 2001; Figure 2b). Other non-forest cover types, for example cropland, can show different water use. However, areas potentially available for CEF in the Southwest Goulburn are indeed likely to be grazing lands and therefore this assumption is probably valid. The catchment studies included in the analysis will have varied widely in grassland management, climate, soil and catchment attributes. The average error of estimate (RMSE) of mean annual grassland water use was 75 mm (Zhang *et al*., 2001; Figure 2b). Given the wide variety in grassland characteristics even within the Southwest Goulburn, it is questionable whether more accurate water use estimates can be obtained.

3.5. Links between land cover, productivity, soil and (geo-) hydrology

Soil infiltration and water retention capacity are usually increased after afforestation (e.g. Bruijnzeel, 2000). Furthermore, links can be expected between the suitability and productivity of a certain soil type for forestry on the one hand, and the hydrological properties of that soil and even the groundwater flow system (GFS) underlying it on the other. As a result, both land cover and forest productivity may correlate to the partitioning of excess rainfall into quick near-surface flow pathways and groundwater recharge, and perhaps also to the characteristics of the underlying GFS.

The latest BC2C model version does include some of the effect of land cover on soil hydrology, by changing the fractions of excess rainfall infiltrating and running off superficially, respectively. However this approach could not yet be validated (Dawes and Gilfedder, in review). Unfortunately at present knowledge of the interaction between vegetation and soil hydrological processes is limited and the interaction between the many factors affecting them too diverse and complex to allow a more sophisticated description in hydrological models (Bruijnzeel, 2000).

4. Spatial forest expansion scenarios

4.1. Introduction

The effects of afforestation on catchment-scale hydrology will be influenced both by the total area planted and the location of plantations. The potential area for successful CEF is constrained by the following factors:

- the land available for afforestation;
- the requirement that afforestation reduces stream salinity;
- the forest production rates that can be realised;
- other economic considerations, importantly transport and processing costs and the intrinsic value of produced wood;
- other environmental benefits or disbenefits that may accrue from afforestation. At present, only changes in stream flow and salinity were considered, but future research will aim to also include maintaining or improving biodiversity and carbon sequestration.

Not only the total area of plantation forest is relevant, but because hydrological impacts vary spatially, forestry establishment targeted to particular areas can also affect catchment level outcomes differently. For example, forest expansion might target the most productive areas or those closest to processing facilities first. If these coincide with relatively wetter areas, then the decrease in stream flow inherent to afforestation will also be greater than if expansion was random and catchment stream salinity might also be affected differently. Correlations between productivity and stream flow and salinity impacts can indeed be expected because of the natural links between topography, (hydro-) geology, soils and climate (see Section 3.5).

4.2. Potentially available area

The previous hydrological modelling exercise for the Southwest Goulburn provided some insights into the relative importance of the mentioned constraints, with the exception of those associated with the economics of transport and processing. Some results are summarised in Table 2.

The non-forested area was determined from 25 m resolution satellite images (see Section 2). Each 25 m pixel was classified as covered by trees or not on the basis of its light reflecting properties. Subsequently, the classified pixels were aggregated to 100 pixel blocks (i.e. 250m × 250 m) and if >20 out of 100 pixels were classified as trees, the block was taken to be covered with forest. Although this approach is expected to produce accurate hydrological modelling results at the catchment scale, classification uncertainty does affect its use to determine whether a particular block is actually forested or not. For example, a very sparse forest or a forested block with anomalous spectral properties may have been classified as non-forest. Conversely, non-forest land cover types with spectral properties resembling those of forest may also have been wrongly classified.

Table 2. Summary of the hydrological and productivity modelling results for the Southwest Goulburn (Van Dijk *et al.*, 2004). Areas with sufficient productivity were defined as areas for which *Pinus radiata* productivity modelling (Booth et al., in press) suggested mean annual increment rates >15 $m^3\ ha^{-1}$, whereas water yield and stream salinity changes were calculated for 15 years after afforestation.

	Area (km^2)	Fraction of catchment	Fraction of non-forested area
Total area	3,742		
Non-forested area	2,433	65%	100%
Water yield loss	2,433	65%	100%
Sufficient productivity	1,339	36%	55%
Salinity benefits	463	12%	19%
Salinity benefits and productive	453	12%	19%

The total area of non-forested land estimated from satellite data was 65% of the total Southwest Goulburn catchment area (Table 2). This is an overestimate of the area likely or even potentially available for commercial forestry, as it will include public land, conservation areas, cropland, residential areas, and so on. GIS-based information available within the project and from its partners and consultations with stakeholders are being incorporated in the SPIF framework to identify areas potentially available for afforestation in a more realistic manner. This also acts to improve the realism in the hydrological model results, but does not place any additional requirements on the way plantation scenarios are defined.

Afforestation reduced water yield in all cases (Table 2), reflecting the fact that forests use more water than lower vegetation types. Because stream runoff is always reduced after afforestation, the relative decrease in salt discharge into streams needs to be greater to produce a stream salinity decrease (i.e. the concentration of salt in stream flow). Fifteen years after afforestation of the non-forested land in the Southwest Goulburn catchment this was expected to be the case for 463 km^2, covering 12% of the catchment or 19% of the non-forested area (Van Dijk *et al*., 2004). Forest productivity constraints reduced the area potentially available to CEF by only 10 km^2 (Table 2).

4.3. Targeted expansion strategies

Expansion of the area of plantations can be considered as driven by changes to external factors influencing a landholder's decisions. These factors can include forestry companies offering contracts to land owners to grow and manage plantations on private lands; or subsidies or other incentives offered by governments to landowners or forestry companies to locate plantations on specified land for public benefit. For the second case, these lands can be specified at three levels:

1. The incentive is granted for any land in a particular district. For example, these districts could cover a contiguous area of ~200,000 ha, within which planting may be random.

2. The incentive is granted for any land afforested within the area with predicted true stream salinity benefit. This may result in random planting over the recognised 46,300 ha with expected benefits.
3. The incentive is granted differentially for lands with salinity benefits, and is commensurate to the expected stream salinity benefit. This could result in a spatially distributed expansion that targets stream salinity reduction most efficiently.

We investigated correlations between site afforestation and salinity reduction, water yield and site productivity. All areas with expected salinity benefits after 15 years (250×250 m blocks, 463 km^2 in total; Table 2) were ranked based on one of three criteria: decreasing salinity benefit, increasing water yield loss or decreasing productivity. Subsequently, three different scenarios were run, each designed to target afforestation based on one of these criteria. For each scenario it was assumed afforestation would proceed in order from the highest-ranked to the lowest-ranked block. For example, for the scenario targeted at maximising the salinity benefit, it was assumed the block with the highest salinity benefit would be planted first. This also means that the overall effectiveness decreases with every additional block being planted. The cumulative effect on the ranking variable and the other two variables was calculated. For the ranking variable, this shows the magnitude of spatial variation and hence the effectiveness of a targeted planting strategy. For the remaining two variables, a straight line suggests that there is no correlation with the ranking variable. A straight line should also result if expansion occurs in a completely random fashion. A curve above the line implies a positive correlation with the ranking variable, whereas a negative correlation will be reflected in a curve below the line. It is noted that this exercise does not address the mentioned possibility that planting is random but within designated districts. This scenario can be included in future model applications.

Figure 3 shows the cumulative impact on stream salinity, stream flow and forest productivity for the corresponding three targeting scenarios. If the total 463 km^2 were to be planted, after 15 years salinity is predicted to be reduced by 0.9 $\mu S\ cm^{-1}$ and water yield by 12.0 GL y^{-1}, while total forest productivity is expected to be $1.6 \times 10^5\ m^3\ y^{-1}$ (Van Dijk *et al*., 2004). The cumulative effects were expressed as a percentage of these numbers.

It appears that targeted planting to maximise salinity benefit can greatly increase its effectiveness: for example, 50% of the maximum achievable effect can be realised by afforesting only 20% of the potential CEF area (i.e. 93 km^2 or 2.5% of the catchment; the dark blue and green areas in Figure 4). This result illustrates the importance of targeting new plantation development in areas where salinity benefits can be expected to be greatest. Targeting plantations to maximise salinity benefits was predicted to have only minor consequences for total water yield loss and productivity: these curves are close to the straight line and are therefore not strongly correlated to salinity benefits (Figure 3a).

If plantation expansion is targeted to minimise water yield losses, a different picture appears (Figure 3b). The effectiveness of such an approach appears limited and the maximum difference in water yield loss between random and targeted planting is 12% or ~700 ML y^{-1}, occurring when roughly half of the available area is planted (Figure 3b). Somewhat surprisingly in view of the expected relationship between water use and productivity (Section 3), the model did not suggest a relationship between water yield loss and productivity. This suggests rainfall was not the main constraint to modelled forest productivity within the area considered. The relationship with salinity reduction is more complex. The actual locations corresponding to different parts of the curve were had with different combinations of rainfall and groundwater flow system. The initial steep increase

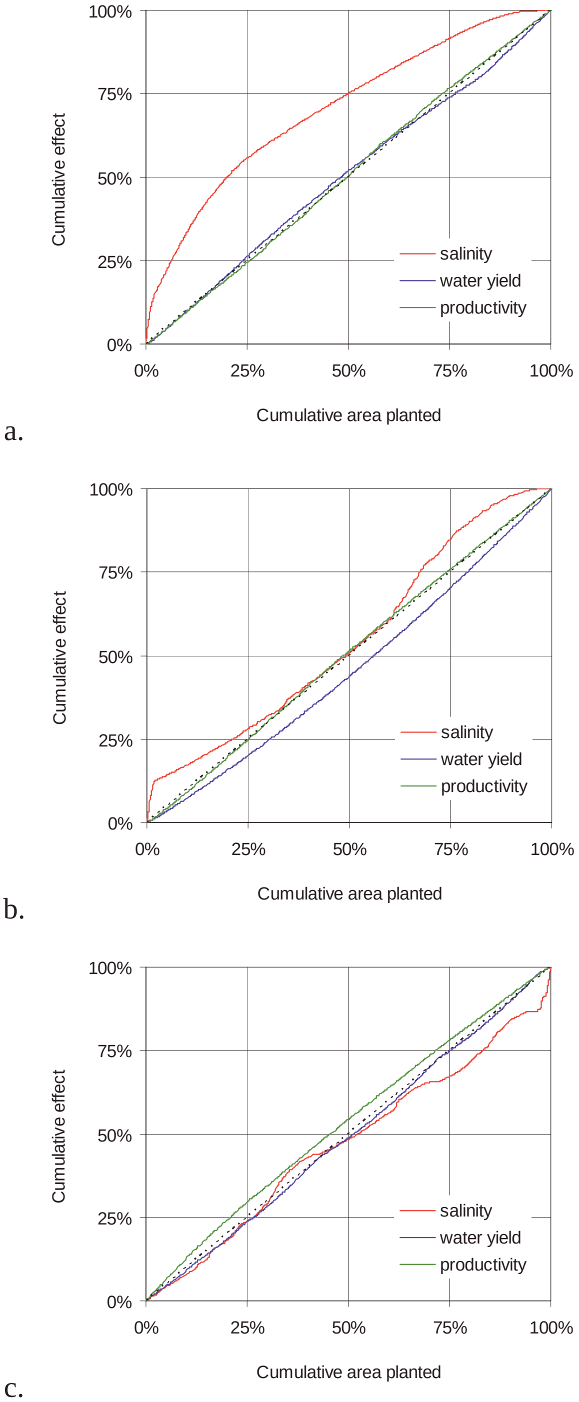

Figure 3. The cumulative relative effect on stream salinity decrease, water yield decrease and forest productivity in the Southwest Goulburn for plantation expansion strategies intended to (a) maximise salinity benefits, (b) minimise water loss or (c) maximise productivity. Note that the percentage of area planted relates only to areas where salinity benefits are expected (463 km^2 in total).

in salinity reduction in Figure 3b coincides with a number of localised fast responding local groundwater flow systems in low rainfall areas in the northern part of the catchments (Figure 4). Water use is less in these areas and therefore water yield loss is also limited,

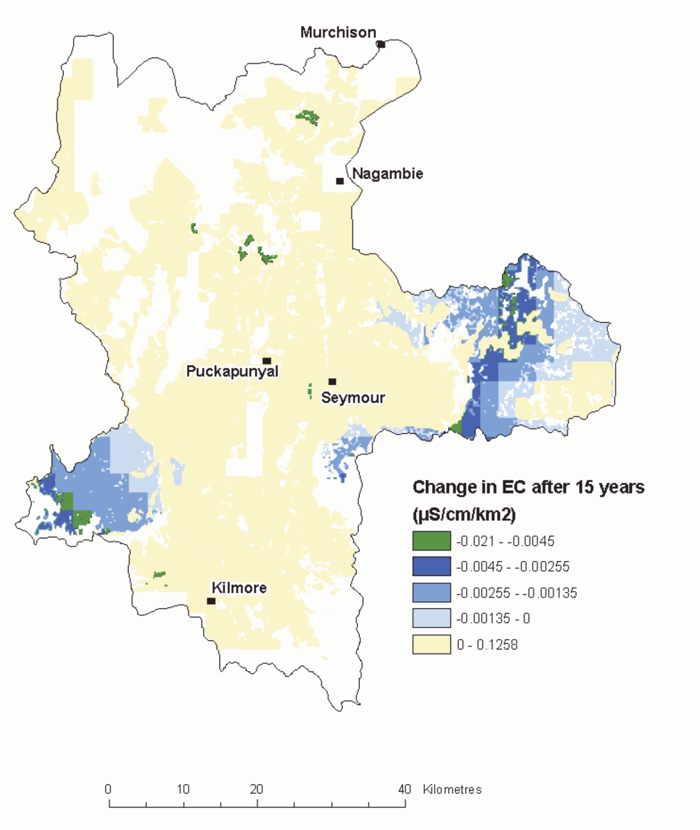

Figure 4. Illustration of the large spatial differences in the expected effectiveness of afforestation to reduce stream salinity. Afforestation in the yellow area is modelled to lead to either no change or an actual increase of stream EC after 15 years. The four other coloured areas when fully afforested would each reduce stream EC by 25% of the maximum achievable effect (cf. Figure 3a).

while the fast response of the groundwater system ensures a relatively rapid reduction in salinity.

Forest productivity is also least in these areas, and this explains the last, steep part of the cumulative salinity curve when planting is targeted to maximise productivity (Figure 3c). For the remaining area potentially suitable for CEF (97%), there does not appear to be a systematic relationship between productivity and salinity benefits. The effectiveness of this expansion strategy in maximising productivity appears even less than that for minimising water yield loss. When compared to random plantation expansion, targeted planting can improve total production by $7.2\times10^{3}\ m^{3}\ y^{-1}$ or 5% of the total achievable production at most, occurring after 43% of the area is planted (Figure 3c). Again, there is no apparent relationship between productivity and water yield loss.

It should be stressed that these results are only preliminary. The modelled water use does not take account of forest characteristics and management. A link between the forest growth and hydrological models may result in a stronger correlation between productivity and water use. Also, use of a different evaluation time frame instead of the 15 years used in this model application can change the conclusions. Finally, more accurate and detailed information on soil and GFS properties will also influence the shape of the curves in Figure 3. These three issues are being addressed in ongoing development of the hydrological model and SPIF.

Expansion strategies targeted to minimise other constraints to successful CEF were not tested at this stage. These might include, for example, strategies to:

- minimise transport costs by planning forestry operations near mills and access roads;
- maximise biodiversity benefits, for example by connecting remnant areas of native vegetation or planting along river courses; and
- maximise other environmental benefits, such as carbon sequestration, soil conservation and/or rehabilitation of degraded land.

The nature and value of some of these strategies will be investigated in future within the CEF project in consultations with local and general experts on hydrology, forestry and economy and stakeholders, including state governments, catchment management authorities, forest industry representatives and private and corporate investors.

5. Conclusions

5.1. Introduction

The overall aim of this report was to assess how different scenarios for commercial environmental forestry development in the Southwest Goulburn can be converted in a form suitable for modelling stream salinity and stream flow impacts.

Specific aims were to (1) identify the data requirements of the current hydrological modelling approach; (2) investigate the plantation characteristics that can be represented in hydrological modelling, now or in the near future; (3) identify the factors determining the potential area suitable for CEF and investigate the spatial correlation between these factors.

5.2. Hydrological model input requirements

The representation of land cover on hydrology in the BC2C model is currently limited to its effect on water use. It uses so-called 'Zhang curves': empirical relationships between rainfall, potential and actual evapotranspiration for broad vegetation types by comparing over 250 global catchment studies (Zhang *et al*., 1999; 2001). These relationships only make a distinction between forest or non-forest cover.

Consequently, the hydrological modelling requires only information on the spatial distribution of new plantations. It places no further data requirements on the definition of scenarios. This provides simplicity in scenario definition and modelling, but prevents exploration of potential differences between alternative forest species or management regimes.

5.3. Representation of forest characteristics and scope for improvement

The approach of Zhang *et al*. (2001) does not describe the influence of forest characteristics such as forest composition, age, productivity, thinning and stocking density. These have a potentially important effect on water use and therefore may need to be described in future model versions.

The statistical catchment data analysis approach taken by Zhang *et al*. (2001) will not be suitable to describe the impact of forest characteristics on water use, although meta-analysis techniques may help overcome some problems related to sample size. A promising way forward is provided by the recognition that the water use of Australian eucalypt forests is strongly linked to leaf area (Hatton *et al*., 1998; Benyon *et al*., 1999, 2001). Therefore, water use differences caused by forest characteristics should correspond to LAI differences. In as much as LAI is described by the forest growth model to be used within the SPIF (3PG, Landsberg and Waring, 1997), there is good scope to relate this to water use.

There are links between land cover, geology, hydrology, soil and climate that are not described within the hydrological model but still do affect the impact of afforestation on stream salinity. The quantitative understanding of these links appears insufficient at present to be described in the model however.

5.4. Spatial forest expansion scenarios

The area potentially available for commercial environmental forestry is constrained by the area of land not already forested; the fact that salinity benefits cannot be realised everywhere; and forest production rates. Based on these criteria, 12% of the Southwest Goulburn catchment was estimated to be suitable for CEF (Van Dijk *et al*., 2004).

The potentially available area and its spatial distribution will be different in reality, because of uncertainty in land cover classification, and because not all land will be available for private forestry investment. Economic considerations (e.g. transport distance) will impose further constraints, whereas other environmental impacts, for example related to biodiversity, carbon sequestration and land degradation, can also positively or negatively influence CEF opportunities. Future work in developing the SPIF will include additional GIS-based information and stakeholder consultation to improve the degree of realism and completeness in these respects.

To investigate the spatial correlation between stream salinity benefits, water yield loss, and forest productivity, we quantitatively compared forestry expansion strategies designed to maximise salinity benefits, minimise water yield losses, or maximise forest production, respectively. This was done using the results of previous hydrological impact and forest productivity modelling for the Southwest Goulburn catchment (Van Dijk *et al*., 2004; Booth *et al*., in press). When compared to random expansion, this exercise suggested that planting targeted to maximise stream salinity can substantially improve efficiency, apparently without having any markedly different impact on water yield loss or production. This result highlights the importance of selectively targeting those areas where salinity benefits are greatest to optimise the effectiveness of new plantations.

By comparison, planting targeted to minimise water yield loss or maximise wood production appeared less efficient. The most noted effect on stream salinity reduction was related to the occurrence of a few localised fast responding groundwater systems in the drier north of the Southwest Goulburn. Future model applications using an improved representation of forest hydrology, different boundary conditions (e.g. longer time scales) and more accurate and detailed soil and geohydrological information may change these conclusions, however. In addition, other expansion strategies may be included as scenarios in future, for example targeted to minimise transport costs or to maximise other environmental benefits. These alternative scenarios will be defined in consultation with experts and stakeholders.

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 of DAFF, Lu Zhang and Alice Best of CSIRO Land and Water, and Bob McCormack and Gavan Thomas of CSIRO Forestry and Forest Products for their useful comments and suggestions.

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