

An empirical, comparative model of changes in annual water yield associated with pine plantations in southern Australia

Leon Bren^{1,2}, Patrick Lane¹ and Don McGuire³

¹School of Forest and Ecosystem Science and CRC for Forestry, The University of Melbourne, Creswick, Victoria 3363, Australia

²Email: l.bren@unimelb.edu.au

³ForestrySA, Jubilee Highway East, Mount Gambier, South Australia 5290, Australia

Revised manuscript received 17 May 2006

Summary

Results from three Australian multiple catchment projects that examine the change in water yield on conversion from native eucalypt forest to radiata pine were combined. The projects were located in southern Australia near Myrtleford (Victoria), Daylesford (Victoria) and Bathurst (NSW). From these data a model of change in water yield relative to the eucalypt forest was derived using age and annual rainfall as independent variables. This model was extended to derive estimates of change in water yield from grassland sites converted to radiata pine by using the model of Zhang *et al.* (2001) to estimate the difference in water use between native forest and grassland. The results showed (and quantified) that conversion of native forest to radiata pine usually increases water yield but conversion of grassland sites to radiata pine usually decreases yields. Increased water yields are associated with young pines and high rainfalls, while decreased water yields are associated with older pines and low rainfalls. The models were tested using data from radiata pine plantations planted on grassland sites in Tumut (NSW), Kilmore (Victoria) and 'fynbos' in South Africa. In general the models performed reasonably well in estimating sequences of changes in flows. Estimates of total water yield were less accurate. Heavy or frequent thinning may be a source of change that may need to be accounted for separately if the details of this are known. The derived models may be useful in estimating the comparative changes of flow associated with the development of multiple blocks of radiata pine plantations on catchments. This can be programmed in a spreadsheet.

Keywords: models; water balance; rain; flow; age; radiata pine

Introduction

Radiata pine (*Pinus radiata* D. Don) is a major plantation species in the southern hemisphere, and is planted in areas of Mediterranean climate with an annual rainfall ideally in the 600–1500 mm range. Historically, Australian plantations were made by clearing native forest. In the last two decades this has become unacceptable on environmental grounds. A consequence of this has been that plantations are now made by purchase and planting of grasslands. In turn, this has caused considerable concern about

the impact of these plantings on local and regional water balances. This reflects a sequence of dry years with chronic water shortages across much of southern Australia (Keenan *et al.* 2004). Concerns about the reductions of water flow emanating from land converted to forestry plantations have been expressed in other countries with major plantation developments (e.g. Sahin and Hall 1996; Scott *et al.* 1998; Sikka *et al.* 2003; Keenan *et al.* 2004; Lane *et al.* 2004; Jackson *et al.* 2005). In some studies of possible flow changes, the 'forest–grass' evapotranspiration–rainfall comparative relationships of Zhang *et al.* (2001) have been used to provide estimates of the water use by plantations. These give estimated evapotranspiration of forest and grassland as functions of rainfall, but do not include the age of the forest. While useful, such comparative curves may be misinterpreted as they represent transpiration by forests with an unknown range of site occupancies. As young plantations do not have full site occupancy, these relationships may overestimate plantation water use. In most Australian conflicts the concern has been with possible changes in yield affecting existing water user entitlements rather than the actual quantity of flow.

This paper presents an empirical model of the changes in annual water yield of a catchment converted from eucalypt to radiata pine as a function of annual rainfall and age of the plantation. This model is based on data obtained from three Australian multiple-catchment studies. By combining this with a model of the difference in water yield between grassland and 'forest', the model is extended to give estimates of the change in water yield when grasslands are converted to radiata pine. Additionally, use of evapotranspiration estimates of grassland and forest combined with the water yield–age–rainfall relationship developed below allows estimates (albeit of a lower accuracy) to be made of the catchment yield of radiata pine as a function of age and annual rainfall. The models derived are tested by application to radiata pine plantations on research catchments in Australia and South Africa. The quality of fit is used to give estimates of the reliability and error of the model. It is anticipated that the model will be of use in estimating the impact of a proposed radiata pine development on water yield from a catchment given a knowledge of area and age of the plantations in the catchment.

The basis of the model

A simple water balance formulation

Consider a catchment water balance measured over a year:

$$P = ET + S + \Delta m + \varepsilon, \quad (1)$$

where P = annual precipitation (mm), ET = annual evapotranspiration (mm), S = annual streamflow (catchment yield) (mm), Δm = increase in soil moisture over the period of measurement (mm), ε = error in measurement, including deep seepage (loss due to groundwater processes) (mm).

If the period of measurement is taken between times of similar flow and seasonal conditions, then the change in soil moisture can, at the cost of some error, be viewed as negligible and ignored. Similarly scientists normally assume that the error term, ε , is small relative to the other measurements and can be ignored. Given this, with rearrangement, (1) reduces to:

$$S = P - ET. \quad (2)$$

For southern Australian radiata pine plantations, P can be taken as rainfall since snow and other forms of precipitation are negligible in the water balance. This basic partitioning of received rainfall into either streamflow or evapotranspiration underpins the computations of this paper.

The Zhang model of forest and grassland annual evapotranspiration

Zhang *et al.* (2001) presented evapotranspiration (ET) of forest and grassland as a function of annual rainfall (P). Their curves were derived from a world-wide study of forest and grassland runoff using data from 250 catchments. The curves are shown in Figure 1 for the range of rainfalls used for radiata pine plantations. Zhang *et al.* (2001) state that 'the model is a practical tool that can be readily used to predict the long-term consequences of reforestation, and has potential uses in catchment-scale studies of land use change'. Their discussion includes a comprehensive consideration of the errors induced, and notes that the variation can be substantial, with root-mean-squares of error in the 70–90 mm range. The curves can be expressed as:

$$\text{Forest: } ET_{\text{forest}} = \left(\frac{1 + (2820/P)}{1 + (2820/P) + (P/1410)} \right) P; \quad (3)$$

$$\text{Grassland: } ET_{\text{grass}} = \left(\frac{1 + (550/P)}{1 + (550/P) + (P/1100)} \right) P. \quad (4)$$

In the paper of Zhang *et al.* (2001), this relation refers to grass, but sometimes the synonym of pasture or hermland is used. ET refers to annual evaporation (mm) and the subscript 'grass' or 'forest' defines the type of vegetation community. More generally, for catchments with mixtures of forest and grassland, a weighted average would be used:

$$ET = (1 - p_{\text{frac}})ET_{\text{forest}} + p_{\text{frac}}ET_{\text{grass}}, \quad (5)$$

where p_{frac} is the fraction of grassland in the catchment, and the catchment is assumed to comprise only forest and grassland.

For convenience in later discussion, we have defined the difference in evapotranspiration between an area of grassland and an area of forest for a given rainfall (Fig. 1) as:

$$\Delta ET_{\text{forest-grass}} = ET_{\text{forest}} - ET_{\text{grass}} = S_{\text{grass}} - S_{\text{forest}}, \quad (6)$$

where S_{grass} and S_{forest} are the annual runoff (mm) from an area of grassland and forest respectively. This value would be positive under all rainfalls.

Sources of plantation-change hydrologic data

The basis of our model of water use of radiata pine is the results from three Australian multiple-catchment projects. These examined the changes in annual yield in converting eucalypt forest to radiata pine. Figure 2 shows the location of the projects referred to in this paper. Of these, Croppers Creek, Stewarts Creek and Lidsdale sites were used in model formation. Two catchments in Australia at Red Hill (NSW) and Pine Creek (Victoria), and three catchments in South Africa, were used to provide verification and independent estimates of likely error. Our selection of sites for derivation of the model was necessarily restricted because, as far as we know, these are the only areas for which annual rainfall and annual change-of-flow data following conversion from native forest to radiata pine are available. In most cases the data were obtained from numeric files provided by researchers. For the Lidsdale catchment, data were taken off published graphs with a digitizer because the original data files were not available. In evaluating the model, we have used all catchments for which (to the best of our knowledge) annual data sets involving a change of land-use to radiata pine are publicly available. Table 1 summarises information on the catchments.

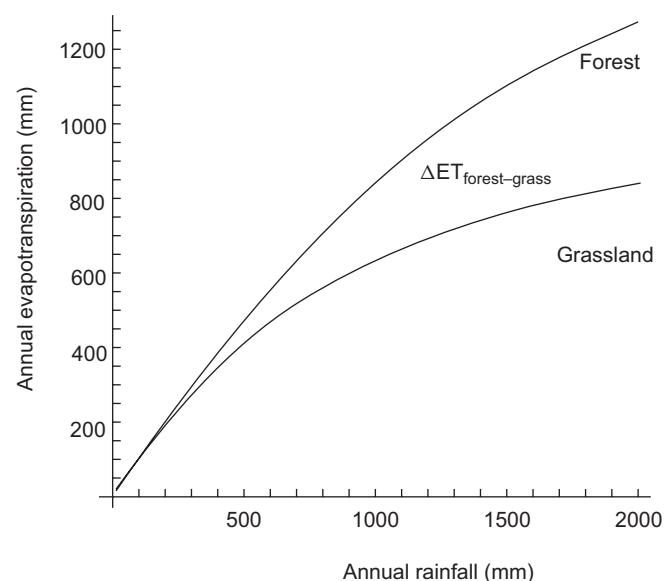


Figure 1. Comparative evapotranspiration curves of Zhang *et al.* (2001) for forest and grassland

Table 1. Projects and catchments providing data for this paper

Project and/or catchment	Area (ha)	Control?	Years of data	Mean annual rainfall (mm)
Croppers Creek Project (Clem Creek catchment)	46.4	Yes	15*	1401
Lidsdale Project	9.4	Yes	16	737
Stewarts Creek Project	17.6	Yes	26	1183
Red Hill Project	195	Yes**	8**	930
Pine Creek Project	320	No	11	787
Jonkershoek Project (SA)				
Biesievlei catchment	201	Yes	35	1281
Lambrechtsbos A catchment	31	Yes	19	1126
Lambrechtsbos B catchment	66	Yes	33	1120

*The catchment was unmeasured from 1987 to 1997

**There is no 'calibration' year; data later than 1997 are currently not available

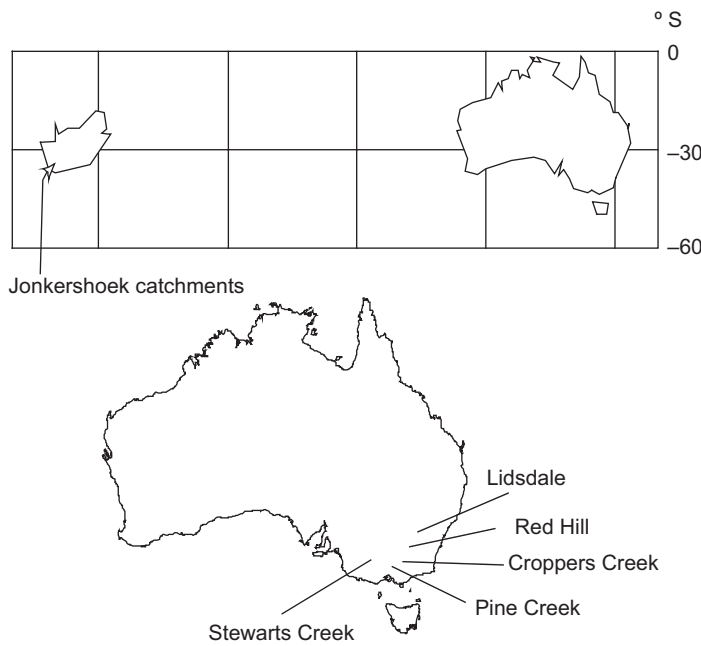


Figure 2. Locations of the research catchments in Australia and the Jonkershoek research catchments in South Africa (relative to Australia)



Figure 3. View of Clem Creek catchment with its adjacent eucalypt forest control. This is typical of the Australian experimental catchments on which this paper is based.

Croppers Creek Project, Australia (model formation)

More detailed accounts of the Croppers Creek Project are given elsewhere (Bren and Papworth 1991; Bren and Hopmans 2006). The project is a multiple-catchment experiment located about 22 km south-west of Myrtleford (Victoria). At the time of their establishment in 1975 all three catchments carried native vegetation. This was a mature, mixed age, mixed species, dry sclerophyll eucalypt forest with no history of forest harvesting. In 1980 Clem Creek catchment (46 ha) had its slopes converted to radiata pine plantation by removal of the native eucalypt forest. Figure 3 gives a view of this catchment after conversion to pine. It can be seen that a 30 m buffer strip of native eucalypt forest was left along the stream, resulting in 93% of the catchment being converted to pine; the increase in flow observed was correspondingly scaled up by multiplying by 1/0.93 (in the other two projects referred to below no riparian strip was left). To minimise the effects of changes in water storage, the observational year is from 1 May to 30 April. At this time of the year flows in Clem Creek are about the lowest experienced, thereby minimising error in the use of the water balance equation.

The gap in the flow sequence between 1988 and 1997 is because the managing agency ceased data measurement in 1987. Subsequently measurement resumed in 1997 with support from the plantation industry. From the point of view of this project, the gap reduced the number of annual data points available by ten, but it has not otherwise impaired the integrity of the data.

Lidsdale Project, Australia (model formation)

Putuhena and Cordery (2000) published an account of the 'Lidsdale Project' located near Bathurst (NSW). This involved measurement of changes in water yield when a dry sclerophyll eucalypt forest catchment was completely cleared and converted to radiata pine. The catchment had an area of 9.4 ha, with an average slope of 12% (about 7°). Measurement commenced in 1959. In 1978 the catchment was cleared and planted with pine. The results presented examine the impact of the conversion on stemflow, throughflow and storage capacity of the forest floor litter, and ultimately streamflow. Details of the eucalypt forest are not given.

Stewarts Creek Project, Australia (model formation)

Stewarts Creek Project was located near Daylesford (Victoria). Results from this have been reported in Mein *et al.* (1988), Nandakumar (1993) and Lane *et al.* (2005). The treatment examined the effect of complete conversion from mixed-species eucalypt forest to radiata pine plantation on a catchment of 17.6 ha. Available results cover the period from 1961 to 1990. The eucalypt-to-pine conversion occurred in 1969 with a thinning operation in 1991. The original forest was a regrowth dry sclerophyll forest resulting from logging at the end of the 19th century.

Red Hill Project, Australia (model verification)

The Red Hill Project of State Forests of NSW followed the changes in runoff from an area of grassland at Tumut that was converted to radiata pine. Details of the project are given by Major *et al.* (1998), and results are given by Hickel (2001) and Lane *et al.* (2005). The 195-ha Red Hill catchment was converted from grassland to radiata pine in 1988 (50 ha) and 1989 (145 ha). The neighbouring 135-ha Kileys Run catchment was used as a control. Data for recent years are not available publicly and, at the time of writing (2006), error issues with the data post-1997 were being addressed.

Pine Creek Project, Australia (model verification)

Pine Creek emanates from a 320-ha catchment between Kilmore and Broadford in south central Victoria. The area is undulating to steep. The catchment consisted of open grassland that in 1986–1987 was reforested with radiata pine. In 1988 a gauging station was installed by the then Rural Water Commission to observe changes in flow. The pines have grown well. Lane *et al.* (2005) have shown a decline in flow from this stream as the trees have grown. A data sequence from 1988 to 2000 (flow and rainfall) was available. The quality of measurement of the data and errors in the data are unknown, and there is no control catchment.

South African Catchments (model verification)

Data on the change of flow associated with conversion from fynbos to radiata pine in three catchments from the Jonkershoek Project in South Africa were used. Table 2 gives details of these catchments. The data were provided by D.F. Scott (Department of Watershed Sciences, Okanagan Campus, University of British Columbia, *pers. comm.* to Pat Lane). Van Wyk (1987) provides a rainfall–streamflow curve for fynbos which is close to the ‘grassland’ line of Zhang *et al.* (2001). Thus, for the purpose of this paper, we have equated fynbos (a proteaceous shrub woodland) with pasture.

Table 2. Details of the South African catchments converted from fynbos to *Pinus radiata* and used in the verification of the model (van Wyk 1987; Scott *et al.* 2000)

Catchment	Area (ha)	Treated
Biesievlei	201	1948
Lambrechtsbos A	31	1972
Lambrechtsbos B	66	1964

Methods

For each of the three Australian multiple-catchment projects the annual increase in yield ($\Delta S_{\text{eucotopine}}$) following the conversion of a eucalypt catchment to radiata pine was computed by comparison with the neighbouring control catchment. We do not deal with the derivation of these estimates here, but the amount of data used and the computation were substantial. The data can be characterised as:

- Clem Creek (1–7 y and 18–25 y). Rainfall ranges from 800 to 2101 mm y⁻¹.
- Stewarts Creek (1–27 y). Rainfall ranges from 657 to 1570 mm y⁻¹.
- Lidsdale (1–14 y). Rainfall ranges from 494 mm to 961 mm y⁻¹.

In each case the native forest replaced was a dry sclerophyll forest with a variable logging history. Clem Creek had no history of harvesting. Stewarts Creek and Lidsdale both had histories of utilisation many years before conversion, but full details of the eucalypt forest cover are not given in published accounts.

The model fitted can be conceptually described as:

$$\Delta S_{\text{eucotopine}} = F(P, A), \quad (7)$$

where $\Delta S_{\text{eucotopine}}$ (mm) is the annual change in water yield from an area converted from eucalypt to pine, and $F(P, A)$ denotes an appropriate function of the annual rainfall P (mm) and plantation age A (y). A positive value of $\Delta S_{\text{eucotopine}}$ infers an increase in flow. Various model forms were tried with the aim of deriving a model which was ‘well-behaved’ and reasonably simple over the data domain. In this we were guided by the Akaike Information Criterion (Akaike 1973), which is a measure of the trade-off of reduction in error compared to the complexity of an equation attributable to introducing an additional term.

The model derived (equation (7)) was extrapolated to compute the effect of a plantation on streamflow, when a grassland catchment is converted to radiata pine, by use of the equation:

$$\Delta S_{\text{grasstopine}} = \Delta S_{\text{eucotopine}} - \Delta ET_{\text{forest-grass}}, \quad (8)$$

where $\Delta S_{\text{grasstopine}}$ is the increase in water yield (mm) when an area is converted from grass to pine. Additionally, the empirical model was extended to give an absolute measure of plantation water yield by:

$$S_{\text{pine}} = (P - ET_{\text{forest}}) + \Delta S_{\text{eucotopine}}, \quad (9)$$

in which S_{pine} (mm) is the annual water yield of an area of pine plantation. In this equation the term in brackets can be viewed as the streamflow emanating from native (eucalypt) forest for a given annual rainfall. The second term, $\Delta S_{\text{eucotopine}}$, gives the change in flow when the native forest is converted to radiata pine.

To test (8) and (9), estimates were made of the changes in flow where pasture or fynbos had been converted to radiata pine and annual rainfall and flow data were available. The estimates were then compared with either the changes in flow or the actual flow. Catchments included were:

- Red Hill (Australia — change of flow with pasture to radiata pine)
- Pine Creek (Australia — measured flow with pasture to radiata pine)
- Lambrechtsbos A and B (South Africa — change of flow from fynbos to radiata pine)
- Biesievlei (South Africa — change of flow from fynbos to radiata pine).

In each case the comparison first involved deriving the modelled estimate of flow or flow change and plotting this against the measured flow or flow change. Evaluation of the model ‘fit’ followed the findings of Legates (1999) in using the ‘coefficient of efficiency’ and the ‘index of agreement’ to evaluate errors. The coefficient of efficiency (E) is defined by:

$$E = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}, \quad (10)$$

where O_i and P_i are the observed and predicted values respectively, and summation is across n values. The values range from minus infinity (poor model) to 1.0 (perfect model). A value of less than zero indicates that the observed mean gives a better estimate than the model used.

The index of agreement (d) was computed by

$$d = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}. \quad (11)$$

The index of agreement varies from 0 (poor model) to 1 (perfect model).

Legates (1999) suggests that model evaluation should include an absolute measure of error. For this the root mean square error (RMS) was computed by:

$$RMS = \sqrt{\frac{\sum_{i=1}^n (y_{est} - y_{obs})^2}{n}}, \quad (12)$$

where y_{est} and y_{obs} are the estimated and observed values of annual flow (mm), n is the number of years of observations, and summation is over all years of the data.

Results

Derivation of the flow change model

Figure 4 shows the change in annual water yield associated with conversion of native forest to radiata pine plantation for the three sites. Regression analysis of the change in yield as a function of age and rainfall yielded the following relationship ($R^2 = 0.82$):

$$\Delta S_{\text{euctopine}} = 12.269P^{0.5} + 13.436A - 144.745A^{0.5}, \quad (13)$$

where $\Delta S_{\text{euctopine}}$ is the increase in annual streamflow (mm) when an area of native forest is converted to radiata pine, A is the age of the pines, and P is the annual rainfall. A positive value of

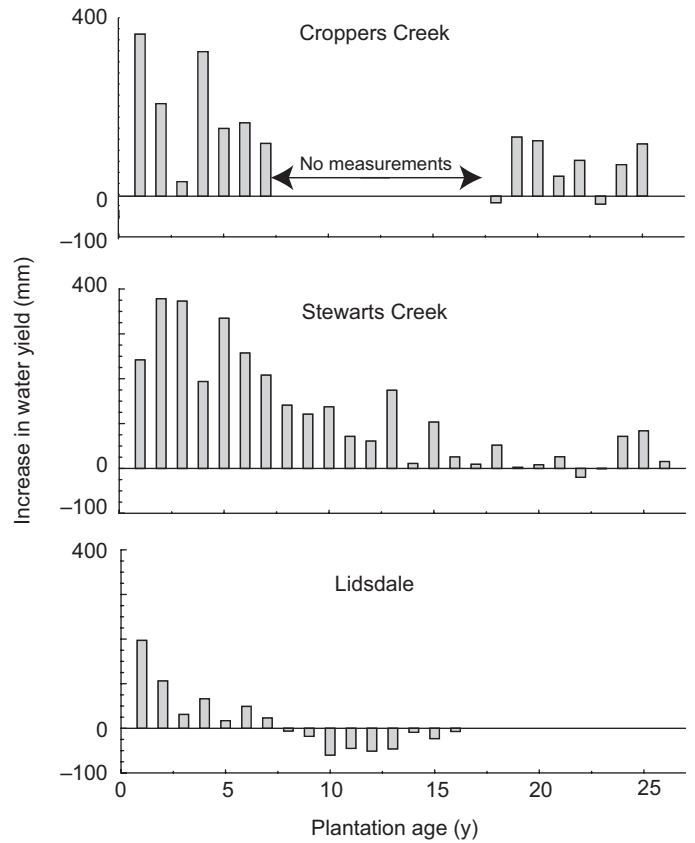


Figure 4. Change in yield on conversion from eucalypt to pine at the three Australian experimental sites as a function of the age of the plantation

$\Delta S_{\text{euctopine}}$ means an increase in streamflow. All the coefficients are significant at the 5% probability level. The relationship is entirely empirical — inclusion of the terms $P^{0.5}$ and $A^{0.5}$ serves to increase the fit of the equation but they have no theoretical significance. This relationship is shown in Figure 5(a) as a three-dimensional view, and in Figure 6(a) as a contour-plot. The results suggest that, for most situations, the radiata pine plantation yields more streamflow than native forest. In particular, the combination of young trees and high rainfall leads to substantially greater runoff than the native forest. Correspondingly, as the trees age, or in years of low rainfall, the runoff diminishes below that of the native forest. Clearly thinning and other silvicultural treatments alter the magnitude of such effects but there were inadequate data for the inclusion of these in the model. We discuss the matter of thinning in some detail below.

Substitution of the appropriate terms in (8) gives an estimate of the change in water yield in converting an area from grassland to pine:

$$\begin{aligned} \Delta S_{\text{grasstopine}} &= - \left[\frac{(1 + (2820/P))P}{(P/1410) + 1 + (2820/P)} \right] \\ &+ \left[\frac{(1 + (550/P))P}{(P/1100) + 1 + (550/P)} \right] \\ &+ 12.269P^{0.5} + 13.436A - 144.745A^{0.5}. \quad (14) \end{aligned}$$

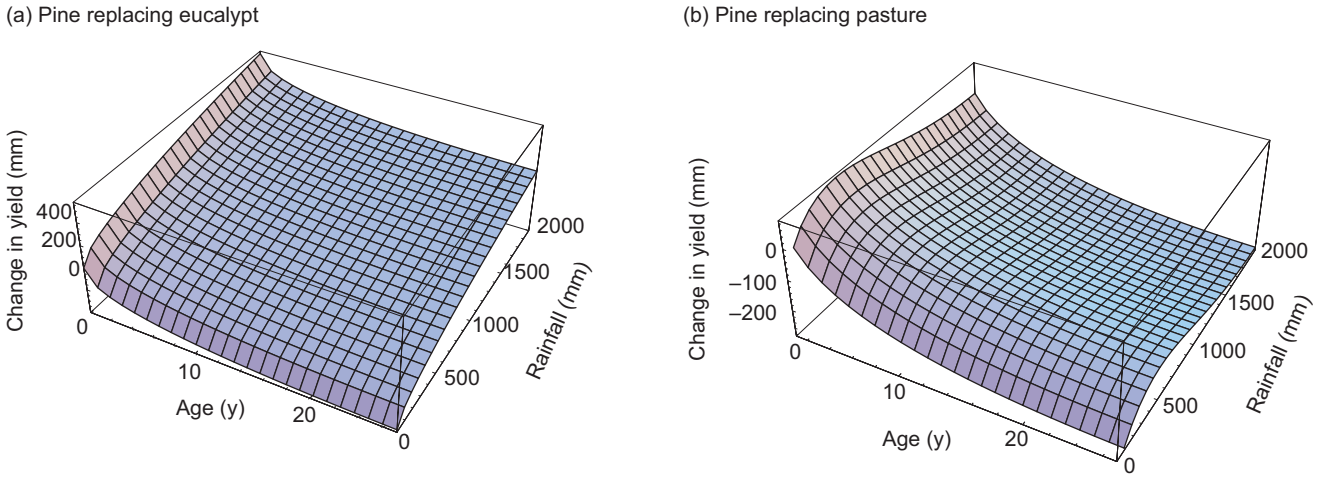


Figure 5. Change in water yield as a function of age and annual rainfall for radiata pine (a) replacing eucalypt and (b) replacing grassland

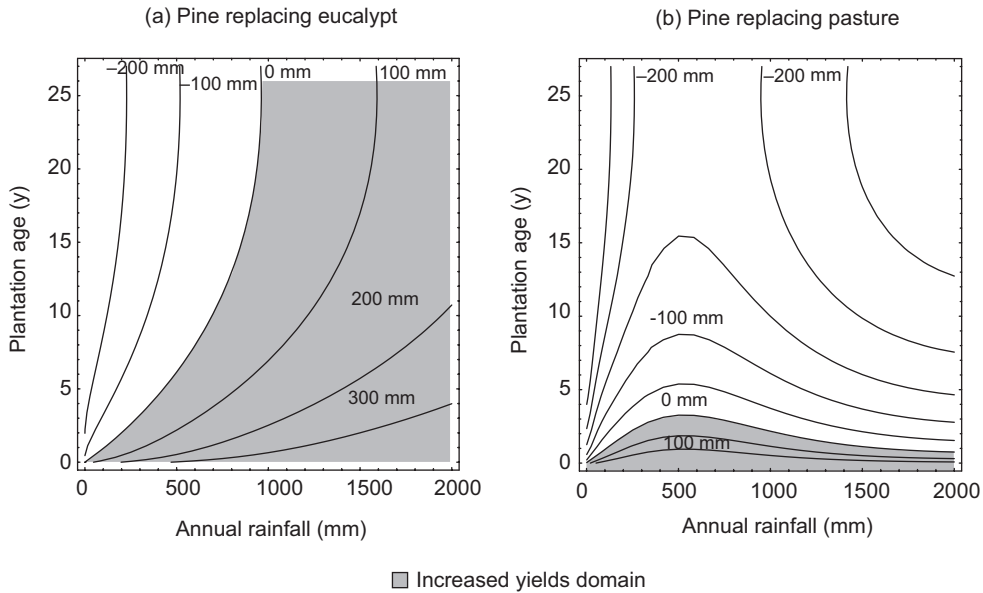


Figure 6. Contour plots showing change in water yield as a function of age and annual rainfall for radiata pine (a) replacing eucalypt and (b) replacing grassland. Contours are at 100 mm intervals in (a) and 50 mm intervals in (b). The shaded area indicates the domain of increased water yield relative to the original land use.

Figure 5(b) (3-D plot) and Figure 6(b) (contour plot) show the estimated change in water yield (mm) when grassland is converted to radiata pine. The results suggest that very young plantations (0–2 y) will yield more water than grassland. As the trees age, the relative water use increases and the yield drops substantially below that of grassland catchments. Interestingly the results suggest that the greatest reduction in water yield attributable to plantations planted on grassland sites is associated with high rainfall and older trees. This reflects that, at lower rainfalls, the water yield of grasslands is close to zero.

Stream flow from radiata pine plantations

Substitution of (3) and (13) in (9) yields:

$$S_{\text{pine}} = P - \left(\frac{1 + (2820/P)}{1 + (2820/P) + (P/1410)} \right) P + 12.269P^{0.5} + 13.436A - 144.745A^{0.5}, \tag{15}$$

where S_{pine} is the annual yield of water from a block of radiata pine (as a function of annual rainfall P , and age A) in mm. Figure 7 shows annual water yield (mm) from a radiata pine plantation as a function of annual rainfall for different plantation ages. The estimated streamflow given by the ‘grassland’ and ‘forest’ curves of Zhang *et al.* (2001) are also included for comparison. The results show:

1. A plantation of age 0 y (effectively bare ground) has the highest water yield.
2. At about age 2 or 3 y the plantation streamflow is about equivalent to that of grassland.
3. At age 9 y the plantation streamflow is about midway between the grassland curve and the forest curve of Zhang *et al.* (2001). Within the range of data, the water use of the radiata pine plantation as a function of age does not appear to increase much beyond this point.

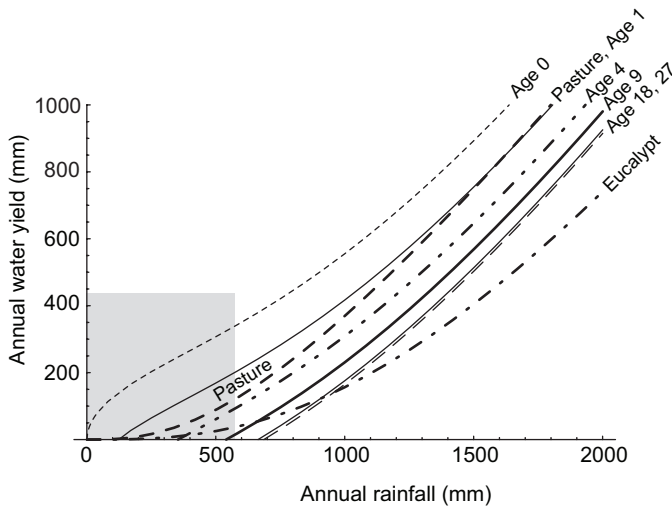


Figure 7. Water yield of radiata pine plantations as a function of rainfall for different ages. For comparison the grassland ('pasture') and forest ('eucalypt') lines of Zhang *et al.* (2001) are also shown. The shaded area is included for completeness but is an extrapolation of the data.

4. Except perhaps at rainfalls below 800 mm y⁻¹, the plantation water yield is greater than that of the native forest which it replaced.

The reader is cautioned against drawing inferences at low (i.e. less than 500 mm y⁻¹) rainfalls from these models. In particular, the use of polynomials can introduce substantial curvature in regions towards the extremes. The models derived have been made to behave gracefully at the low end of the rainfall range (shaded area, Fig. 7), but it is acknowledged that relative errors become large at the lower end of the rainfall spectrum.

Verification of the flow models using Australian data

Red Hill Project: hydrologic change

Figure 8 shows the fit of the grassland-change model used to estimate the change of flow at Red Hill (grassland site) for the short sequence of publicly-available data. With the exception of

1994 (noted as having 'very low rainfall' — 415 mm y⁻¹) the model behaved reasonably. Given very low flows in both the control and the planted catchment in this year, it may be that there was no 'buffer store' of water to allow the pines to transpire more than the grassland (i.e. both the grass and the pine transpired all available water). The large flow observed in 1996 also appears anomalously high relative to the rainfall but there is no information provided on this. Unfortunately more up-to-date data from this project is not publicly available pending a review of aspects of measurement.

Pine Creek Project: streamflow from the catchment

Figure 9 shows the results of the model applied to Pine Creek catchment. Because there was no control catchment we can, in this case, only model the total water yield in successive years as the radiata pines developed. The model reproduces important features of the data but is not a satisfactory fit. The absolute yield of the catchment tends to be over-estimated by the 'grasslands' component of the model. Because there is no control we have no knowledge of the component attributable to pine compared to that attributable to the annual rainfall. However, the model does reproduce well the diminishing yield of the catchment.

South African data: changes in the streamflow

Figure 10 shows the model applied to three South African conversions to radiata pine. In general the model reproduces the increase in flow over fynbos at very young ages and the decreasing streamflow as the pines age. We regard the agreement as quite reasonable for a model of this simplicity.

Errors in the models

For satisfactory use of the model, estimates of the likely error involved in estimates are useful. We are unaware of any models similar to this for evaluating the effects of radiata pine on catchment hydrology, so we cannot usefully compare our results with those from other models. Our estimates of the coefficient of efficiency, index of agreement, and root mean square error for each of the above cases are given in Table 3. A useful ranking of

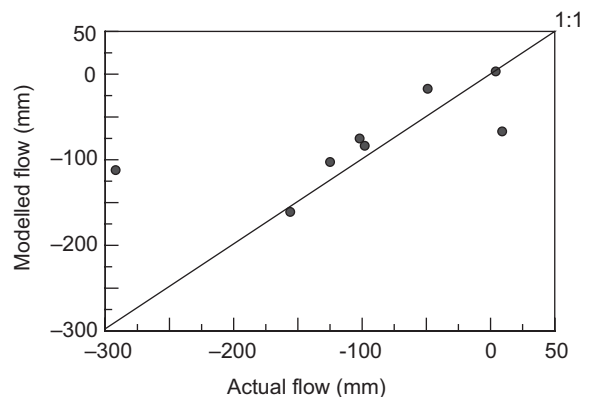
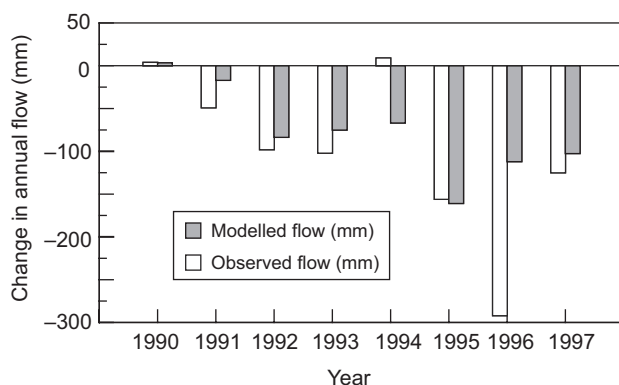


Figure 8. Observed and modelled change in yield at Red Hill site

the error in the three models presented in this paper can be given as:

- Smallest error: equation (13) (i.e. change in water yield in conversion from native eucalypt forest to pine), being directly derived from experimental data.
- Increased error: equation (14) (i.e. change in water yield from

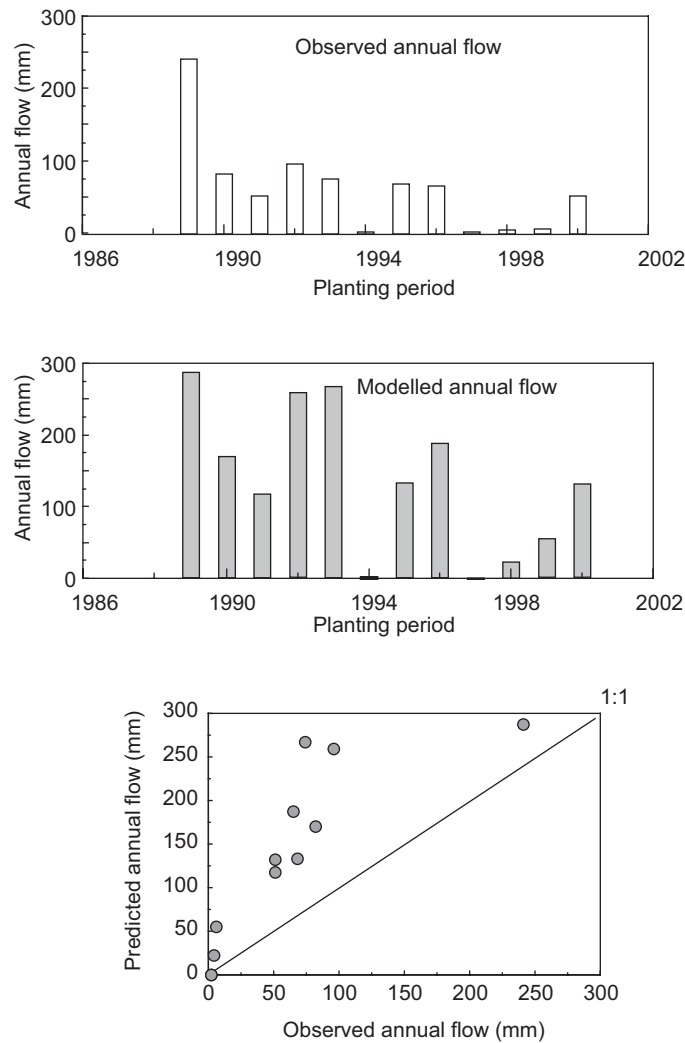


Figure 9. Observed and predicted yield of Pine Creek catchment after planting in 1986–1987

pasture sites to pine). This combines the error of equation (13) plus the error involved in the difference between the ‘grass’ and ‘forest’ curves. The model has utility and appears to show the relative time sequence, but would seem to be not always accurate in the absolute measure of change.

- Maximum error: equation (15) (i.e. water yield from radiata pine catchment). This involves the absolute error in the models of Zhang *et al.* (2001) together with the error of equation (13). The application of the model at Pine Creek is an example. The model has minimal predictive ability for this situation but can be useful in the absence of other estimators.

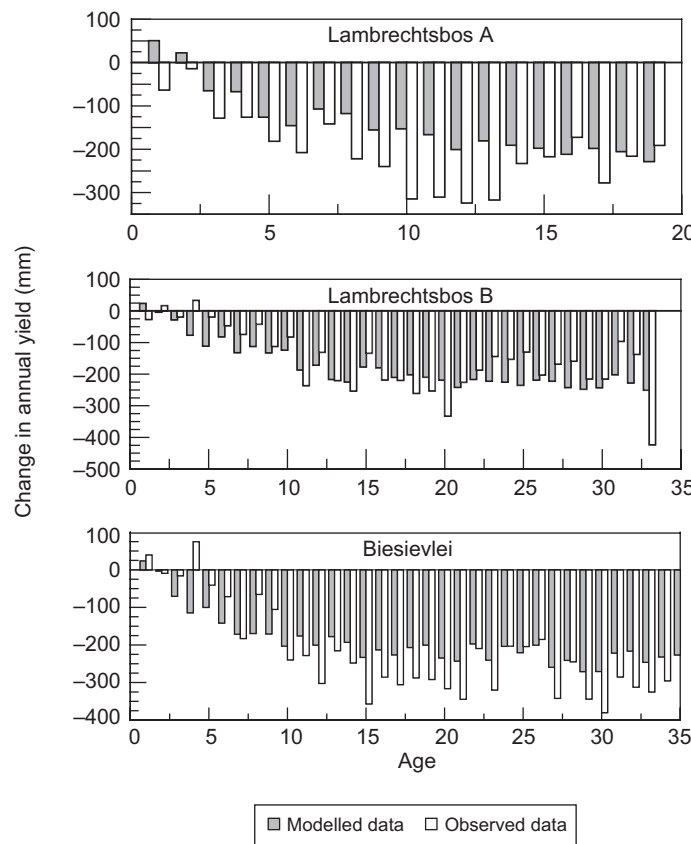


Figure 10. Comparison of modelled and observed results for the Jonkershoek catchments

Table 3. Coefficient of efficiency, index of agreement, and root mean square error of the model data and the verification models used

Type of model	Data source	Coefficient of efficiency (<i>E</i>)	Index of agreement (<i>d</i>)	Root mean square error (mm)
Equation (13) (change from eucalypt to pine)	Clem Creek*	0.55	0.80	77
	Stewarts Creek*	0.76	0.89	56
	Lidsdale*	0.31	0.89	54
Equation (14) (change from pasture to pine)	Red Hill	0.38	0.79	68
	Biesievlei	0.49	0.81	81
	Lambrechtsbos A	-0.51	0.67	96
	Lambrechtsbos B	0.59	0.83	63
Equation (15) (total yield from pine)	Pine Creek	-1.26	0.47	95

*Used in model formation

Clearly there is some variation in the quality of agreement of the model. Overall the model performs about as well as well-known examples of hydrologic models (Thornthwaite, Jensen-Haise, and van-Bavel models) used by Legates (1999). Zhang *et al.* (2001) give the root mean square error of their widely-used models for forest and grass as 93 mm and 75 mm respectively, so the errors shown in Table 3 are of about similar accuracy (although in our case the average error for forest was slightly less than for grass); realistically this reflects about the level of accuracy possible with such simple variables and field measurement.

We conclude that the models perform well when estimating the change in runoff from clearing a eucalypt catchment, and perform adequately but to a lesser accuracy in estimating the change in runoff associated with afforestation of an agricultural catchment. The model should not be used for estimating absolute yield unless there is little choice.

Discussion

Impacts of thinning on the water yield

There is solid evidence of the impact of thinning on the water yield of plantations — a typical response would be an additional 100 mm in the first year and 50 mm in the second year after thinning, with the response dying away as the trees fill the gap (e.g. Scott and Lesch 1997). The last 3 y of yield increase at Stewarts Creek (Fig. 4) show a thinning effect of this magnitude. Croppers Creek data can perhaps be interpreted as showing an increase associated with thinning, but it is confounded by low rainfall. Ultimately we did not have adequate thinning data to include this in our model. The data do suggest that the coincidence of dry years suppresses any yield increase associated with thinning. Manipulation of stand density by thinning may change the relative amount of runoff for 1–2 y afterwards.

Total catchment yield of mixed-land-use catchments

A common request in Australia is to assess the effect of a pine plantation on catchment water yield. Usually potential changes in water yield are of far greater concern than the total water yield. There is usually little or no measured data. Modelling requires a collection of information on the amount of native forest and grassland, and for each year the age of each block of plantation. In some cases a synthetic sequence of future rainfalls must be generated. The modelling then entails a systematic application of either equation (13) (eucalypt to pine) or (14) (grass to pine) to each block to compute the change in runoff, multiplication by area to convert to volume, and summation of the total of these for each year to give the estimated effect. In situations where there are large areas of young plantations and rainfall is high, the plantations will give a net increase in streamflow. As the plantations age the net change tends to be a decrease in streamflow. Ultimately the arithmetic becomes a series of debits and credits, and an agreed 'averaging' over time is required since, as an older plantation block is harvested, it goes from producing reduced runoff to producing increased runoff (relative to other uses). The periodic harvesting of plantations produces a cyclicity in streamflow yields. Ultimately the modelling becomes a spreadsheet exercise in accounting. The concept is illustrated in Figure 11.

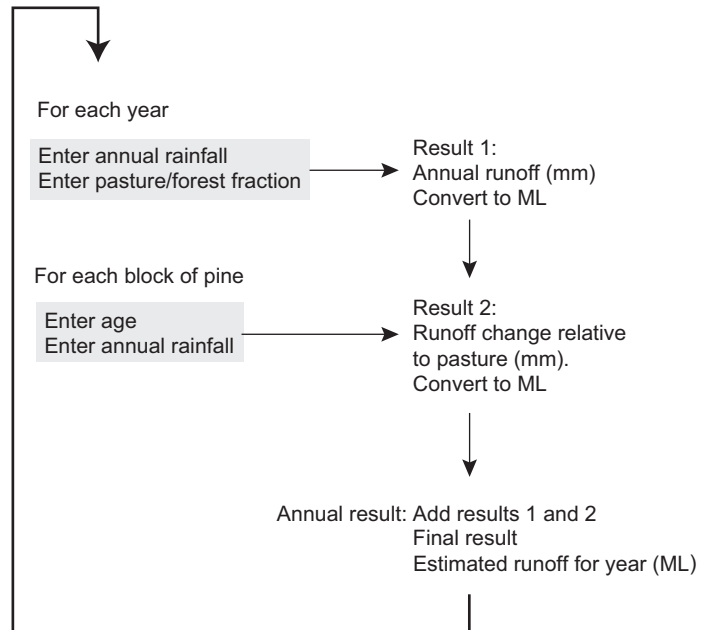


Figure 11. Schema showing how the model is applied to a larger catchment

The details of such a model application is beyond the scope of this paper; but a spreadsheet illustrating this and showing the inter-conversion of units necessary is available from the senior author on request. Such a model can be a useful tool for coming to grips (quantitatively) with the water impacts of plantations on a larger catchment. The information needed for a given year is the area by age class for each block of radiata pine. As necessary, an explicit provision for thinning could be made in such a model provided the information on the basal area change was available. In using this we have many caveats on the accuracy of such an approach, but these tend to reflect the lack of knowledge of the hydrologic effects of crops other than radiata pine. A notable feature of such simulations is the complexity of the pine 'water use' once data from a number of blocks of different rotations and ages are used as input, together with a sequence of predicted annual rainfall.

Our experience has been that such modelling is usually undertaken with little or no hydrologic data. The model presented does give a 'cumulative effects' picture of quantifiable, albeit not particularly high, accuracy, and is useful in such situations. Ideally, modelling would take into account many other factors associated with pines including spatial position on the catchment and many detailed hydrologic characteristics, but at the time of writing this ideal seems a long way from being realised.

Conclusions

The combination of results from the Croppers Creek, Stewarts Creek and Lidsdale studies produced a simple, empirical model of water use of radiata pine compared to native forest. This model uses age of the trees and annual rainfall. When joined with the model of water use of Zhang *et al.* (2001), the model can be used to predict change in annual water yield for sites planted with

radiata pine with reasonable accuracy. In the absence of more complex biophysical models, the model may be a useful tool in the resolution of land use issues where water is of importance.

Acknowledgements

This work is an outgrowth of the Croppers Creek Hydrologic Project supported by Hancock Victorian Plantations, the CRC for Catchment Hydrology, and Forest and Wood Products Research and Development Corporation. We also acknowledge the efforts of the un-named hydrologists who collected and processed the large amounts of data inherent in these hydrologic studies.

References

- Akaike, H. (1973) Information theory and an extension of the maximum likelihood principle. In: Petrov, B.N. and Csaki, F. (eds) *Proceedings of the Second International Symposium on Information Theory*. Adademiai Kiado, Budapest, pp. 267–281.
- Bren, L.J. and Hopmans, P. (2006) Observations on water use of mature eucalypt and immature radiata pine forests in Victoria, Australia. *Journal of Hydrology* (in press).
- Bren, L.J. and Papworth, M. (1991) Early water yield effects of conversion of slopes of a eucalypt forest catchment to radiata pine plantation. *Water Resources Research* **27**, 2421–2428.
- Hickel, K. (2001) The effect of pine afforestation on flow regime in small upland catchments. Masters thesis, University of Stuttgart, 136 pp.
- Jackson, R.B., Jobbagy, E.G., Avissar, R. and ten others (2005) Trading water for carbon with biological carbon sequestration. *Science* **310**, 1944–1947.
- Keenan, R.J., Parsons, M., Gerrand, A., O'Loughlin, E., Beavis, S., Gunawardana, D., Gavran, M. and Bugg, A. (2004) Plantations and water use: a review prepared for the Forest and Wood Products Research and Development Corporation, Bureau of Rural Sciences, GPO Box 858, Canberra, ACT. <http://affashop.gov.au/product.asp?prodid=12974>
- Lane, P.N.J., Morris, J.D., Zhang, N.N., Zhou, G.Y., Zhou, G.Y. and Xu, D. (2004) Water balance of tropical eucalypt plantations in south-eastern China. *Agricultural and Forest Meteorology* **124**, 253–267.
- Lane, P.N.J., Best, A.E., Hickel, K. and Zhang, L. (2005) The response of flow duration curves to afforestation. *Journal of Hydrology* **310**, 253–265.
- Legates, D.R. (1999) Evaluating the use of 'goodness of fit' measures in hydrologic and hydroclimatic model validation. *Water Resources Research* **35**, 233–241.
- Major, E.J., Cornish, P.M. and Whiting, J.K. (1998) *Red Hill Hydrology Project Establishment Report including a Preliminary Water Yield Analysis*. Research Paper No. 36, Forest Research and Development Division, State Forests of New South Wales, Sydney, 24 pp.
- Mein, R.G., Bieniaszewska-Hunter, H. and Papworth, M. (1988) Land use changes and the hydrologic water balance — Stewarts Creek Experimental Area. In: *Hydrology and Water Resources Symposium*. Australian National Conference Publication No. 88/1, Institution of Engineers, Canberra, pp. 129–134.
- Nandakumar, N. (1993) Analysis of paired catchment data to predict the hydrologic effects of land-use changes. PhD thesis, Department of Civil Engineering, Monash University, Melbourne, Australia, 222 pp.
- Putuhena, W.M. and Cordery, I. (2000) Some hydrological effects of changing forest cover from eucalypts to *Pinus radiata*. *Agricultural and Forest Meteorology* **100**, 59–72.
- Sahin, V. and Hall, M. (1996) The effects of afforestation and deforestation on water yields. *Journal of Hydrology* **178**, 293–309.
- Scott, D.F. and Lesch, W. (1997) Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *Journal of Hydrology* **199**, 360–377.
- Scott, D.F., Le Maitre, D.C. and Fairbanks, D.H.K. (1998) Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. *WaterSA* **24**, 187–200.
- Scott, D.F., Prinsloo, F.W., Moses, G., Mehloakulu, M. and Simmers, A.D.A. (2000) Areas-analysis of the South African catchment afforestation experimental data. Report No. 8/10/00, Water Resources Centre (WRC), South Africa.
- Sikka, A.K., Samra, J.S., Sharda, V.N., Samraj, P. and Lakshmanan, V. (2003) Low flow and high flow responses to converting natural grassland into blue gum (*Eucalyptus globulus*) in Nilgiris watersheds of south India. *Journal of Hydrology* **270**, 12–26.
- Van Wyk, D.B. (1987) Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *WaterSA* **13**(1), 31–36.
- Zhang, L., Dawes, W.R. and Walker, G.R. (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37**, 701–708.