Predicting Afforestation Impacts on Monthly Streamflow

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EXTENDED ABSTRACT

Information on the impacts of afforestation on streamflow is important for catchment water resources management. This study presents a predictive method for determining afforestation impacts on monthly streamflow using data from four Australian experimental catchments. The catchments have undergone considerable forest cover change with 21 to 90% of areas afforested. Monthly rainfall, potential evapotranspiration, and streamflow data are available for these catchments, as well as other data including plant available water capacity, minimum and maximum elevations, and index of valley bottom flatness.

The method used in this study is based on a monthly water balance model whose parameters can be estimated from catchment characteristics using projection pursuit regression. To predict the impacts of afforestation on monthly streamflow, the model was calibrated for pre-treatment conditions and afforestation-induced changes in the model parameters were predicted by combining the calibrated model parameter values and projection pursuit regression. The predicted parameter changes are consistent with our current understanding of afforestation impact on catchment water balance and this gives us confidence that projection pursuit regression appropriately identified the effects of forest cover on the model parameters.

Following afforestation, mean annual streamflow in these catchments reduced between 35 to 91%. Despite considerable changes in streamflow, the model was able to accurately predict the impacts on monthly streamflow. The Nash Sutcliffe coefficient of efficiency (E) between measured and predicted monthly streamflow varied between 0.40 and 0.86 and the index of agreement (IA) is greater than 0.65 with root mean squared error ranged from 1.35 to 10.71 mm (see Table 1). The observed and predicted monthly streamflow series for the post-treatment period showed good agreement.

The success of the method indicates that the model represents the key catchment processes and characteristics. Based on the assessment of model parameter changes, increased storage capacity and evapotranspiration efficiency are the key factors responsible for the reduced monthly streamflow observed. The degree of change in the model parameters due to afforestation is also influenced by other characteristics of the catchments and the local climatic conditions.

This study demonstrated the strength of the parsimonious conceptual water balance model and its ability to predict afforestation impacts on monthly streamflow when combined with the parameter estimation procedure. The method can be used for afforestation impact assessment on monthly streamflow.

Table 1. Catchment characteristics and predicted impacts of afforestation on monthly streamflow. E is the Nash Sutcliffe coefficient of efficiency, IA is index of agreement, and RMSE is root mean squared error.

	Batalling Ck	Red Hill Ck	Pine Ck	Traralgon Ck
Area (km^2)	16.6	1.95	3.2	87
Mean annual rainfall (mm)	610	866	775	966
Mean annual E_0 (mm)	1374	1294	1137	1010
Increased forest cover (%)	21	73	90	70
Mean annual flow reduction (mm)	11.66	248.35	134.84	130.95
Mean annual flow reduction (%)	34.9	87.4	91.3	38.8
E for pre-treatment period	0.77	0.70	0.82	0.88
E for post-treatment period	0.74	0.86	0.40	0.81
IA for pre-treatment period	0.82	0.81	0.86	0.85
IA for post-treatment period	0.81	0.85	0.65	0.78
RMSE for pre-treatment period (mm)	2.81	14.51	8.76	10.94
RMSE for post-treatment period (mm)	1.35	1.75	2.38	10.71

1. INTRODUCTION

Plantation forestry is an increasingly important land use in Australia and other parts of the world (Zhang et al., 2007a). There are sound environmental and economic arguments in support of plantation development. There are also potential hydrologic consequences that should be recognized and understood when planning such ventures (Vertessy et al., 2003). Strategically located plantations can have positive hydrologic impacts on dryland salinity through their capacity to reduce groundwater recharge. However, at a time when water resources are under great stress in Australia and globally, it is essential that we anticipate and plan for the impact of afforestation on these resources.

Bosch and Hewlett (1982) reviewed 94 experimental catchment studies to determine the effect of vegetation change on water yield. The review demonstrated that water yield increased following forest reduction and that reforestation decreased water yield. It was suggested that the direction of change in mean annual water yield following forest operation can be predicted. However, no functional relationships relating water yield to vegetation change were provided. This review significantly increased our awareness of the impact of forest operation on water yield and its implications for water security.

Zhang et al. (2001) developed a conceptual framework for estimating catchment scale evapotranspiration with readily available data. The model is based on the theory of Budyko (1958), incorporated the effect of vegetation characteristics, and was supported by data from over 250 catchments worldwide. This model quantified the difference between evapotranspiration from forested catchments and that from non-forested catchments. The model is a robust and practical tool for assessing the impact of afforestation on mean annual water yield. Recently, Brown et al. (2005) provided a critical review of the subject with an emphasis on the impact of vegetation change on seasonal flows. It highlighted knowledge gaps about the impact of vegetation change on streamflow at finer time scale such as monthly.

The purpose of this study was to test a predictive method for estimating afforestation impact on monthly streamflow. A monthly water balance model and a parameter estimation procedure were employed to examine the effects of major plantation development on monthly water balance in four experimental catchments in Australia.

2. STUDY CATCHMENTS AND DATA

Four experimental catchments were selected based on known vegetation change history and long records of streamflow data. Batalling Creek catchment is located in the south-west of Western Australia. The area of the catchment is 16.6 km^2 and the mean annual rainfall is 610 mm with winter-dominated rainfall. The main soil types are clayey silty sand and silty sandy clay. About 50% of the catchment was cleared for agriculture from 1940 to 1970 and reforestation took place in 1985 with eucalyptus covering 38% of the cleared area (Bari and Ruprecht, 2003). Red Hill catchment is located northeast of Tumut in New South Wales. The area of the catchment is 1.95 km^2 with mean annual rainfall of 866 mm. The main soil types are shallow red soils and red duplex. The entire catchment was planted with Pinus radiata in 1988 and 1989 (Major et al., 1998). Pine Creek catchment is a tributary of Sunday Creek in the southwestern corner of the Goulburn River catchment in Victoria. It covers an area of 3.2 km^2 and average rainfall is 775 mm. In 1986 and 1987 the whole of Pine Creek catchment was converted from open grassland to Pinus radiata plantation (Linke et al., 1995). Traralgon Creek is a tributary of the Latrobe River in Victoria with an area of 87 km^2. The mean annual rainfall is 966 mm with winter-dominant rainfall distribution. From the late 1950s, the catchment was 80% planted with Eucalyptus regnans.

Observed monthly streamflow records from these catchments are available for this study. Monthly time series of rainfall and potential evapotranspiration are available for these catchments. Monthly rainfall was aggregated using daily rainfall from meteorological stations within the catchments. Mean monthly potential evapotranspiration was calculated based on the Priestley-Taylor equation (Priestley and Taylor, 1972) and details of the calculation can be found in Raupach *et al.* (2001).

For estimating model parameters, 10 characteristics representing catchment and local climatic conditions were obtained. A sine curve was fitted to monthly means of rainfall and the amplitude of the sine curve was used as a parameter describing the strength of rainfall seasonality. The phase shift of the fitted rainfall sine curve was compared to the phase shift of mean monthly potential evapotranspiration in order to classify rainfall regimes as winter-dominant (6 to 8 months lag) or summer-dominant (-1 to 3 months lag). If the amplitude of rainfall divided by mean annual rainfall is small (<0.02), a non-seasonal rainfall regime was assumed.

Daily rainfall from meteorological stations within the catchments was used for the calculation of conditional (wet day) mean daily rainfall and mean relative dry ratio, given by the number of days without rain divided by 365. Plant available water capacity (PAWC) was calculated from soil properties and topographic data using the method of McKenzie et al. (2000). The area of valley floor was estimated using Multi-resolution Valley Bottom Flatness (MrVBF) analysis with 25 m resolution DEMs (Gallant and Dowling, 2003). The relative valley area was calculated as the proportion of the total catchment area classified as MrVBF class equal or greater than 3. Further characteristics are mean annual rainfall and potential evapotranspiration, as well as minimum and maximum elevation. Finally, the percentage of forest cover in each catchment was included in the analysis. This enables us to investigate the effects of afforestation on monthly streamflow.

3. METHODS

3.1. Monthly water balance model

The monthly water balance model used in this study is a lumped conceptual model with two stores: a near-surface root zone store with direct runoff and storage, and a deeper zone without root water uptake that acts as a linear storage reservoir. The model has 4 parameters describing direct runoff behavior, evapotranspiration efficiency, catchment storage capacity and a slow flow component. It uses a method similar to Budyko's concept of water availability and atmospheric demand (Budyko, 1958) or the concept of "*limits and controls*" (Calder, 1998). Fundamental to this framework is a functional form that represents a smooth transition between supply and demand limits (Fu, 1981):

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^w\right]^{1/w} \qquad (1)$$

where E, P, and E_0 are evapotranspiration, rainfall, and potential evapotranspiration at mean annual timescale respectively, w is a model parameter ranging between 1 and ∞. For the purpose of model calibration, we define $\alpha = 1\text{-}1/w$ so that α varies between 0 and 1. This definition also conveniently associates an increase in α with an increase in evapotranspiration efficiency. More details of this mean annual water balance model are given in Zhang *et al.* (2004).

For consideration of monthly water balance, equation (1) was adjusted for partitioning of water balance components that can be expressed by the principle of demand and supply similar to Budyko's approach. The first partitioning assumes that rainfall in time step t will be partitioned into direct runoff $Q_d(t)$ and the sum of other water balance components:

$$P(t) = Q_d(t) + X(t) \qquad (2)$$

with

$$X(t) = E(t) + R(t) + S(t) - S(t-1)$$

where $P(t)$, $E(t)$, and $R(t)$ are monthly precipitation, evapotranspiration, and groundwater recharge respectively; $S(t)$ is the root zone water storage; $X(t)$ is called catchment rainfall retention and is the amount of rainfall retained by the catchment for evapotranspiration, soil moisture storage and recharge.

When the sum of available storage capacity and potential evapotranspiration is very large, $X(t)$ will approach $P(t)$ as little direct runoff will occur under this condition, while when the sum of available storage capacity and potential evapotranspiration is very small, $X(t)$ will approach the storage and evapotranspiration limits. The partitioning of rainfall can be expressed as:

$$X(t) = P(t)F\left(\tfrac{X_0(t)}{P(t)}, \alpha_1\right) \qquad (3)$$

where $F(\ )$ is Fu's curve – equation (1), $X_0(t)$ is the upper limit for $X(t)$ and is equal to (S_{max}- $S(t\text{-}1)$+$E_0(t)$), in which S_{max} is the maximum water storage in the root zone, $S(t\text{-}1)$ is the soil water storage in time step $(t\text{-}1)$ and $E_0(t)$ is the potential evapotranspiration in time step t, and α_1 is retention efficiency, i.e., a larger α_1 value will result in less direct runoff and more rainfall retention.

From equations (2) and (3), monthly direct runoff is calculated as:

$$Q_d(t) = P(t)\left[1 - F\left(\tfrac{X_0(t)}{P(t)}, \alpha_1\right)\right] \qquad (4)$$

At the monthly timescale, evapotranspiration is dependent on soil water storage at the beginning of the time step $S(t\text{-}1)$ and water availability $W(t)$ can be defined as :

$$W(t) = X(t) + S(t-1) \qquad (5)$$

Evapotranspiration at time step t can be determined from the water availability and potential evapotranspiration similar to Budyko (1958):

$$E(t) = W(t)F\left(\tfrac{E_0(t)}{W(t)}, \alpha_2\right) \qquad (6)$$

where α_2 is a model parameter, representing evapotranspiration efficiency. From equations (2) and (5), recharge is calculated as:

$$R(t) = W(t) - \left[E(t) + S(t)\right] \quad (7)$$

or

$$\frac{R(t)}{W(t)} = 1 - \frac{E(t) + S(t)}{W(t)} \quad (8)$$

Similar to Budyko's curve, partitioning of available water into groundwater recharge *R(t)* is estimated as:

$$R(t) = W(t)\left[1 - F\left(\frac{E_0(t)+S_{\max}}{W(t)}, \alpha_2\right)\right] \quad (9)$$

It can be noted that equation (9) shares a common model parameter α_2 with equation (6) and this is because groundwater recharge is essentially determined by evapotranspiration efficiency. That is, as evapotranspiration efficiency is greater (e.g. larger values of α_2), recharge is diminished.

Finally, groundwater storage is treated as linear reservoir, so that the groundwater balance and baseflow can be calculated as:

$$Q_b(t) = dG(t-1) \quad (10)$$

$$G(t) = (1-d)G(t-1) + R(t) \quad (11)$$

where *G* is groundwater storage and *d* is a constant. Equation (10) represents a linear storage-discharge relationship and constant *d* is commonly called the recession constant (Nathan and McMahon, 1990). The simulated total runoff is equal to the sum of direct runoff and baseflow.

3.2. Relationships between model parameters and catchment characteristics

The method proposed in this study involves prediction of the parameters of the monthly water balance model for each catchment under post-treatment equilibrium conditions. An independent estimation of the model parameters for post-treatment conditions is necessary. Zhang *et al.* (2007b) describes the development of regression relationships between the parameters α_1, α_2, S_{max} and *d* of the water balance model and measured catchment characteristics. The relationships were developed based on projection pursuit regression (PPR), first introduced by Friedman and Stuetzle (1981). PPR reduces the number of dimensions by using projections of high-dimensional predictor spaces and applying an additive model to these projections, resulting in a low-dimensional additive model. Cubic splines were used to obtain the nonparametric form of the regression surface. The model formulation in PPR also covers the effect of possible interactions and hence PPR represents regression relationships by general multi-dimensional regression surfaces. Ten catchment characteristics derived from DEM, soil map/land-use map, and daily meteorological data were included in the analysis.

3.3. Model calibration

The first step in predicting the impacts of afforestation on monthly streamflow is to calibrate the water balance model under the pre-treatment conditions. The model calibration was achieved using observed records of monthly rainfall, potential evapotranspiration, and streamflow for each catchment. A combination of a "global search" (Shuffled Complex Evolution) (Duan et al., 1992) and a "steepest gradient" (Rosenbrock, 1960) method was applied. The calibration procedure provided optimized model parameter values for the pre-treatment period.

3.4. Modeling the impacts of afforestation on monthly streamflow

The calibration procedure described above provided optimized model parameter values for the pre-treatment period. To predict the impacts of afforestation on monthly streamflow, one has to obtain model parameter values under post-treatment conditions. This was achieved by assuming that the catchment characteristics remain the same before and after afforestation, except for forest cover. The model parameter values for both pre- and post-treatment conditions were estimated respectively using the regression relationships developed by PPR. Then the estimated change in each of the four model parameters was superimposed onto the calibrated pre-treatment parameter value to yield the predicted model parameter value for the post-treatment conditions. Finally, the water balance model was run using the predicted model parameter values to estimate monthly streamflow in each catchment for the post-treatment period.

4. RESULTS AND DISCUSSION

4.1. Model calibration for pre-treatment conditions

Figures 1 to 4 show comparisons of observed and calibrated pre-treatment streamflow. The root mean squared error (*RMSE*) for the calibration period was between 2.81 and 10.94 mm (Table 1). These results indicate that the model was able to reproduce monthly streamflow under pre-treatment conditions in all catchments. Accurately reproducing pre-treatment flow gives us confidence in using the model for investigating the effects of afforestation on monthly streamflow.

It appears that the length of calibration period affects the performance of model calibration. For example, Batalling Creek and Traralgon Creek have long pre-treatment records over 10 years and showed smaller relative error in the model calibration. The results for Red Hill Creek and Pine Creek showed larger relative error and both catchments have short pre-treatment periods (e.g. 36 months). In the calibration, it was assumed that the streamflow data during the first 2 to 3 years of plantation development represent pre-treatment conditions, i.e. afforestation had negligible effects on the catchment water balance. The errors for all the catchments are well within the acceptable range and no systematic errors were noted.

4.2. Modeling the impact of afforestation on streamflow

Once the water balance model was calibrated for the pre-treatment conditions, it was run for the post-treatment period to predict the effects of afforestation on monthly streamflow using measured meteorological data. The Nash Sutcliffe coefficient of efficiency (E) varied between 0.40 and 0.86 and the index of agreement (IA) as defined in Legates and McCabe (1999) is greater than 0.65 with root mean squared error ranged from 1.35 to 10.71 mm (see Table 1). The difference between the predicted and observed average annual streamflow over the post-treatment period ranged from 3.83 to 38.6 mm. The relative error in predicted mean annual streamflow varies between 18 to 55%. It should be noted that the large relative error in mean annual streamflow of 55% for Pine Creek occurred under extremely low mean annual flows. In this case, the observed average streamflow is 12.9 mm, while the model prediction is 20.0 mm. In comparison with the pre-treatment average annual streamflow of 148mm in Pine Creek, the overall magnitude of mean annual streamflow reductions is accurately predicted for this catchment.

The observed and predicted monthly streamflow series for the post-treatment period are contained in Figures 1 to 4. It should be noted that these catchments exhibit significant change in monthly streamflow following the afforestation, which the model was able to predict. The statistics listed in Table 1 together with the results shown in Figures 1 to 4 all suggest that the monthly water balance model accurately predicted changes in monthly streamflow following major afforestation.

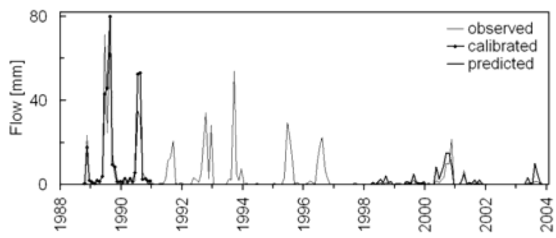

Figure 1. Monthly streamflow for Pine Creek. Pre-treatment period is 1988-1991 and predicted post-treatment period is 1998-2003.

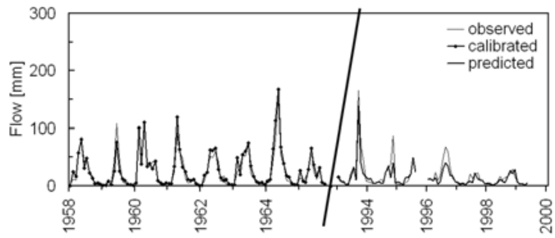

Figure 2. Monthly streamflow for Traralgon Creek. Pre-treatment period is 1958-1965 and predicted post-treatment period is 1993-1999.

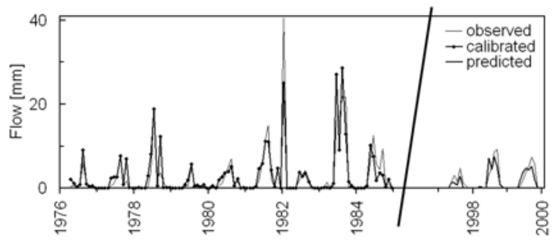

Figure 3. Monthly streamflow for Batalling Creek. Pre-treatment period is 1976-1984 and predicted post-treatment period is 1997-1999.

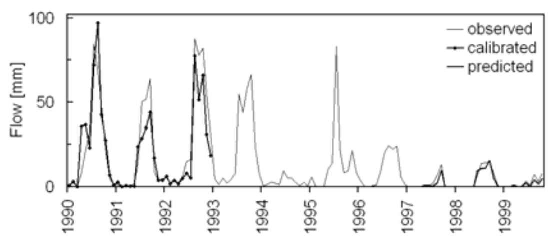

Figure 4. Monthly streamflow for Red Hill Creek. Pre-treatment period is 1990-1992 and predicted post-treatment period is 1997-1999.

The success of the model in predicting the changes in monthly streamflow is dependent on the model structure, input data, and parameter estimation method. In the first instance, the results presented demonstrate the strength of the parsimonious conceptual water balance model in describing key hydrological processes and their combined effects on catchment water balance.

The use of monthly rainfall data is expected to have some impacts on predicted streamflow from the catchments. For Batalling Creek, Red Hill Creek and Pine Creek, monthly rainfall was aggregated using daily rainfall measured near the catchments and they should provide accurate estimates of rainfall for these catchments. For Traralgon Creek, spatially averaged monthly rainfall from SILO was used. Given the relatively large area and relief of this catchment, the use of spatially averaged rainfall may introduce bias in the predicted monthly streamflow. However, it is difficult to quantify the impact, as no measured rainfall data is available for the catchment.

Changes in streamflow can be result from changes in climate and vegetation characteristics (Lane *et al.,* 2005). For predicting the impacts of vegetation change on streamflow, it was assumed that the catchment characteristics remain the same before and after afforestation, except for forest cover. The assumption of time invariant catchment physical characteristics such as soil properties and topography is appropriate. Among the climatic factors, rainfall is generally the most important one affecting streamflow. For Traralgon Creek and Batalling Creek, the mean annual rainfall remains practically unchanged during the post-treatment period and these two catchments showed lower reduction in streamflow following the afforestation. For Pine Creek and Red Hill, mean annual rainfall decreased by 19 and 24% during the post-treatment period and higher streamflow reductions were observed. It should be noted that these two catchments also have greater proportion of area afforested.

In this study, potential evapotranspiration is defined as the energy-limited evapotranspiration or the maximum attainable evapotranspiration in a wet environment, and was quantified using the Priestley-Taylor equation because it provides a physically robust energy-bounded upper limit for the evapotranspiration from terrestrial surfaces (Raupach, 2001). The sensitivity of streamflow to potential evapotranspiration is limited for Batalling Creek, Red Hill Creek, and Pine Creek as they have relatively low rainfall and are water-limited. Streamflow from Traralgon Creek, however, is expected to show greater sensitivity to potential evapotranspiration, as it is more energy-limited.

While the model structure and uncertainty associated with input data may affect the model predictions, the parameter estimation method may have played a more important role because it was used to predict changes in model parameters reflecting the impact of afforestation on catchment water balance. Analysis of changes in model parameters for the post-treatment period indicated that increased storage capacity and evapotranspiration efficiency are the key factors responsible for the reduced monthly streamflow observed. The degree of change in the model parameters due to afforestation is also influenced by other characteristics of the catchment and the local climate.

5. CONCLUSIONS

The hydrology of catchments will undergo significant changes following afforestation. A parsimonious monthly water balance model was applied to four Australian catchments in a range of climatic and geographic settings to quantify the impact of afforestation on monthly streamflow. The results of this study show that the method was capable of accurately predicting changes in mean annual and monthly catchment water balance following various degrees of afforestation in the catchments considered. The successful prediction of the effects of afforestation on monthly streamflow indicates an appropriate model structure and supports the adequacy of the lumped parsimonious model parameterization. The approach presented is potentially a useful tool for assessing afforestation impacts on monthly streamflow at catchment scale.

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