Development and Application of an Operational Model to Assess the Impact of Plantation Forestry on Water Yields

S. Munday[a], R. Nathan[a], C. Daamen[a], and P. Cornish[b]

[a] *Sinclair Knight Merz (rnathan@skm.com.au)*

[b] *Landuse Hydrology Pty Ltd*

Abstract: The economic and environmental benefits offered by plantation forestry are well recognised. However, numerous studies have demonstrated that reafforestation of existing grassland areas is likely to reduce stream flow because evapotranspiration rates are higher from forests. With competing demands for water, it is important that resource managers be equipped with suitable tools to plan and manage such plantations with due consideration of their potential impacts on water yield. This paper describes the development and application of a numerical model specifically for this purpose. The model is capable of simulating average annual changes in catchment yield resulting from changes in land use, natural ageing of forests, and the relative impacts of realistic, user-defined logging schedules. Study catchments are represented by a time-varying mosaic of up to three common land uses – pasture, pine plantation (*Pinus radiata*), and eucalypt forest. Functional relationships describing the relationship between tree age and catchment streamflow were derived from hydrologic data collected from the Red Hill paired catchment experiment in New South Wales. Application of the model to the Adjungbilly catchment in southern New South Wales demonstrated strong agreement between simulated and recorded hydrologic data.

Keywords: Water yield; Forest hydrology; Logging; Modelling

1. INTRODUCTION

The Commonwealth and State governments have committed to trebling the current forest plantation area in Australia by 2020; increasing the area planted to more than 3 million hectares nationally [DPIE, 1997]. Much of the land intended for plantation will involve afforestation of grassland with pines. Such changes in land use can markedly alter the water balance within a catchment. In particular, higher evapotranspiration rates generally mean lower water yields from forested catchments [Holmes and Sinclair, 1986; Cornish, 1989; Ruprecht and Schofield, 1989; Zhang et al., 1999]. In addition, management of a forest for timber production can influence catchment hydrology [Daamen et al., 2001].

The effects of forest management for timber are seen as being important, particularly in catchments where the water resources are already heavily committed. This issue has been an important component of Regional Forest Agreements (RFAs) established in New South Wales [Nathan et al., 2000], and more recently Victoria [Daamen et al., 2001].

This paper describes the development and application of a numerical model capable of simulating temporal yield impacts caused by landuse changes and/or forest management. The model utilises readily available and relatively simple data sets so that it is well suited to use by resource managers.

2. MODEL DEVELOPMENT

2.1 Conceptualisation

The purpose of the model is to simulate temporal changes in streamflow associated with reafforestation of existing grassland and subsequent management of the forest for timber harvesting. The complexity of the model is commensurate with existing scientific knowledge and the available data.

By predefining functional yield response curves for alternative land uses it is possible to limit the model inputs to:

- catchment landuse composition;
- initial forest age profile;

- mean annual rainfall; and
- a forest management model (thinning and harvesting).

Temporal changes in mean annual catchment yield are simulated using these basic inputs.

2.2 Yield Response for Pasture

In temperate environments the evapotranspiration of a mature cover of grass is significantly less than that from a forest [Holmes and Sinclair, 1986; Zhang et al., 1999]. The differences are shown in Figure 1. The key factors for these differences are leaf area, aerodynamic roughness, rooting depth, ability to extract soil moisture in dry conditions, and albedo [Vertessy and Bessard, 1999].

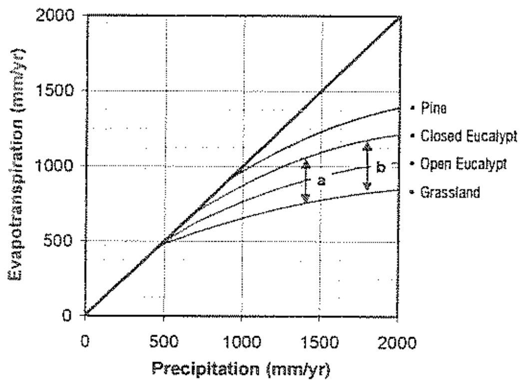

Figure 1. Water use of grassland and mature forest types as a function of rainfall [after Vertessy and Bessard, 1999].

In addition, the time taken for grass to establish is far less than for a tree, usually in the time scale of weeks or months. Thus the impact of grassland on stream flow is considered to be constant for the purposes of simulating mean annual changes.

2.3 Yield Response for Pine Plantations

Research in Australian forest hydrology has concentrated on the yield impacts of Mountain Ash forest and other eucalypt species. Limited information is available for the impact of pine plantations. The few existing studies report that catchments afforested with pines show a larger reduction in water yield than those reafforested with eucalypt species. This Australian finding is attributed to the higher leaf area index and rainfall interception rates of pines [Smith et al., 1974; Pilgrim et al., 1982; Dunin and Mackay, 1982; Cornish, 1989].

A paired catchment experiment was established in 1989 by New South Wales State Forests in the Saw Mill Creek catchment near Tumut (New South Wales, Australia) to provide greater understanding of the yield impacts specifically associated with afforestation of pasture with *Pinus radiata*. A key component of the experiment is streamflow monitoring from two adjacent catchments – Red Hill (reafforested with pines) and Kiley's Run (pasture). Preliminary analyses of the data by Major et al. [1998] and Vertessy [2001] have indicated a reduction in the catchment yield associated with the plantation.

The magnitude and statistical significance of any streamflow trend at this site was further investigated as part of this study. Trend was explored using a Generalised Additive Model (GAM) based on smoothing splines, after accounting for seasonality, climatic influences, serial correlation and non-constant variance [Nathan et al., 1999]. The analysis demonstrated a highly significant trend (at the 5% level) in the catchment yield, declining by 21 mm/yr on average since the establishment of pines in 1989 (Figure 2).

Based upon the known history of the catchment, this trend is solely attributed to afforestation of the catchment with pines and the subsequent ageing of the plantation.

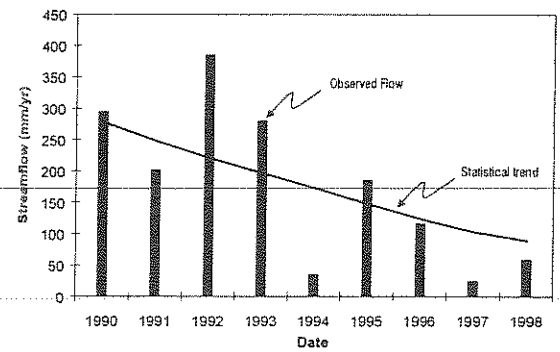

Figure 2. Historic trend in streamflow recorded for the Red Hill catchment.

Comparison of these results (represented as pine water use) with published figures for pine plantations in Lidsdale [Putuhena and Cordery, 2000], and estimates provided by State Forests of New South Wales for Crotty Creek and Red Hill demonstrate good agreement (Figure 3). The higher water use shown for Crotty Creek is to be expected, since this catchment receives higher annual rainfall than the other two catchments.

Unfortunately insufficient data is presently available to define the long-term impacts of a mature pine plantation. For the purposes of simulating a managed plantation this does not present a critical limitation, since pine forest is generally harvested by age 35, before the forest reaches a stage of senescence. Using the results of the GAM analysis, a logarithmic function was fitted to describe the yield response associated with an ageing pine plantation (Figure 4).

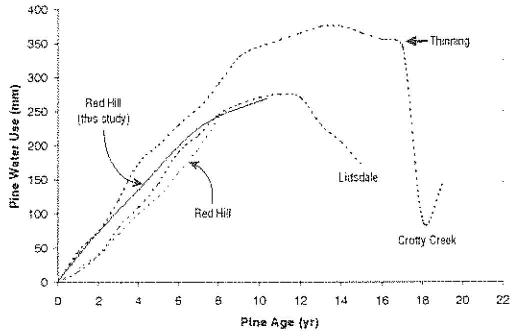

Figure 3. Comparison of water use estimates for different pine plantations.

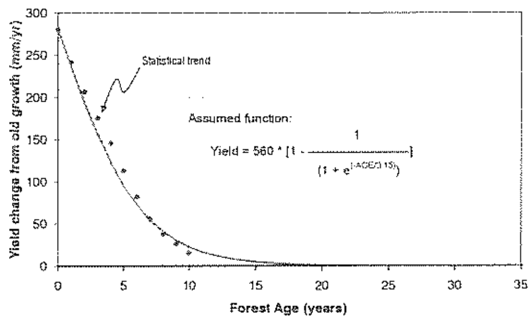

Figure 4. Pine plantation yield response function derived for Red Hill (950 mm/yr average rainfall).

2.4 Yield Response for Eucalypt Forest

A detailed study of Mountain Ash stands in the Maroondah catchment (Victoria, Australia) by Kuczera [1985] demonstrated that the evapotranspiration of a forest progressively increases to a maximum at an age of 20 to 30 years. As the forest continues to age the evapotranspiration gradually declines, eventually reaching a point of equilibrium at maturity. Recent improvements include incorporating an initial increase in streamflow resulting from forest clearance [e.g. Daamen et al., 2001]. The yield response relationship is illustrated in Figure 5. This sort of relationship has been demonstrated in studies of moist eucalypt forests in the Karuah catchments (New South Wales, Australia) by Cornish and Vertessy [2001]. It should be noted that relatively large error bands are associated with these models, particularly for forests aged greater than 50 years, since virtually no recorded data is available in this age range.

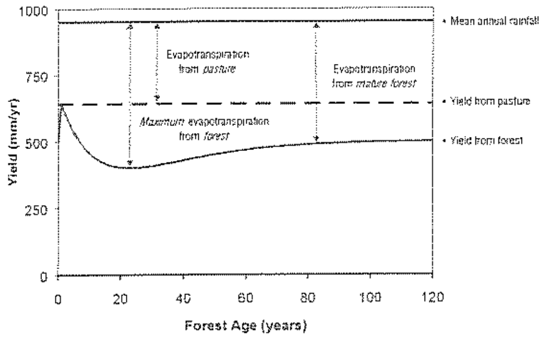

Figure 5. Idealised eucalypt yield response function following clear felling (not to scale).

Cornish [1989] estimated the likely reduction in streamflow resulting from afforestation of both pasture and eucalypt forest with pines for a range of mean annual rainfall conditions (Figure 6). The yield impact estimated for the Red Hill catchment is shown to be in general agreement with the relationships published by Cornish [1989].

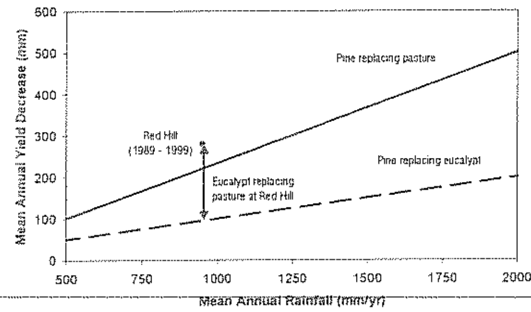

Figure 6. Estimated streamflow reductions arising from afforestation by pines [after Cornish, 1989].

Applying Cornish's estimates in conjunction with the Red Hill data it is inferred that the yield impact of a mature eucalypt forest (relative to pasture) in this catchment is approximately 190 mm/yr. Using this information the idealised curve provided by Kuczera [1985] may be adjusted for the conditions of Red Hill (Figure 7).

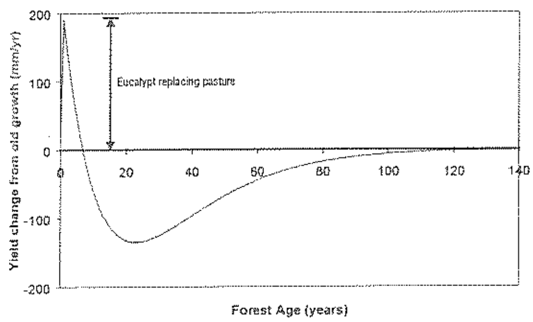

Figure 7. Adopted eucalypt forest yield response function for Red Hill.

2.5 Influence of Rainfall Conditions

It has been well established that the evapotranspiration of a forest increases with increasing mean annual rainfall conditions [Holmes and Sinclair, 1986; Zhang et al., 1999]. It therefore follows that the magnitude of the streamflow response to felling a forest in a high rainfall environment is greater than in a low rainfall one.

Assuming evapotranspiration to be the difference between rainfall and runoff , Vertessy and Bessard [1999] used the work of Holmes and Sinclair [1986] to define individual rainfall-runoff relationships for grassland, open eucalypt forest, closed eucalypt forest, and pines (Figure 1).

The ratio of evapotranspiration rates for a forest relative to that of pasture ('a' and 'b' in Figure 1) may be used to transpose the functional yield response relationships between sites of differing mean annual rainfall conditions. The forest (pine or eucalypt) evapotranspiration rate relative to pasture is used since this equates to the initial yield increase observed when a forest is replaced by pasture (refer Figure 5).

Using this method, a family of curves can be generated for a range of rainfall conditions. As the mean annual rainfall continues to increase forest evapotranspiration reaches a maximum (Figure 1). Therefore, any additional increase in rainfall simply generates excess runoff.

2.6 Catchment Characterisation

The considered land uses are pasture, pine plantation, and eucalypt forest. For the forested regions of a catchment it is likely that there also exist variation in the age class of the trees. To properly account for such spatial variation it is necessary to discretize the catchment into a large number of small cells. Having assigned an initial land use and age class each catchment cell is tracked through time, being subjected to landuse conversion and specified management practices. For the three landuse types there exist six permutations for conversion (eg. pasture to eucalypt, pasture to pines, etc).

2.7 Model Limitations

It is acknowledged that the adopted modelling approach is a simplification of the complex physical processes that occur in reality. Many of these factors, such as soil variability, are inherent in the response factors since they have been developed directly from recorded data. However, since these factors are not explicitly expressed they remain specific to the catchment conditions where the data was collected. Consequently transposition of the curves to other sites introduces error in the estimate. The principal sources of error in the model estimates lie in the defined yield response curves and accounting for the influence of mean annual rainfall differences.

3. MODEL APPLICATION

3.1 Catchment Description

The Adjungbilly catchment (389 km^2) is located in southern New South Wales, southwest of Canberra, and encompasses the Red Hill sub-catchment. Approximately 66 years of streamflow data are available for this catchment, for which about 40% has now been planted with pines. Based upon rainfall contour maps published by the Bureau of Meteorology, the mean annual rainfall for the catchment is 1205 mm/yr.

3.2 Landuse History

The landuse history for the Adjungbilly catchment was re-constructed via interpretation of aerial photographs, topographic maps and a plantation database maintained by New South Wales State Forests. As illustrated in Figure 8, for approximately the first 20 years eucalypt forest was slowly cleared for pasture, with minor areas of pine plantation being established. Following this, significant areas of pasture appear to have been reafforested with pines, with some additional replacement of eucalypt with pines.

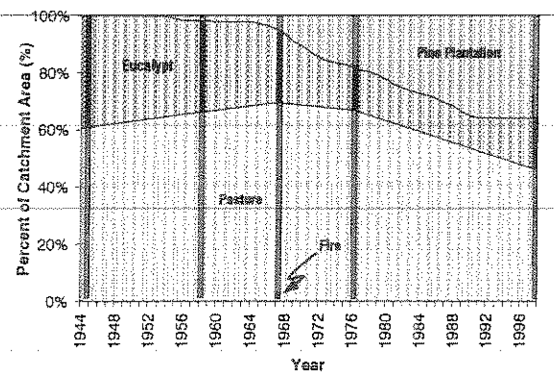

Figure 8. Re-constructed landuse history of the Adjungbilly catchment (recorded data indicated by solid columns).

3.3 Historical Streamflow Trend

The yield response model simulates changes in mean annual streamflow. It is therefore necessary to isolate historical changes in streamflow caused by land use changes from other, often larger, influences, such as climate variability. This enables a meaningful assessment of model performance to be made. Using a Generalised Additive Model (GAM) a second order spline model was fitted, based upon changes in time, rainfall, soil moisture, and seasonality:

$$y = \beta_0 + \beta_1 S\{T;2\} + \beta_2 S\{P;2\} + \beta_3 S\{M;2\} + \beta_4 S\{Sn;2\} + AR1(\varepsilon) \quad (1)$$

where: y is streamflow (ML/mth), β_n are the model coefficients, T is time (mth), P is precipitation (mm/mth), M is soil moisture (mm), Sn is seasonality, and AR1(ε) is the lag-one autoregressive model fitted to the error term.

The analysis indicated that catchment yield increased in time over the period 1933 to the early 1960s, after which it has slowly decreased (Figure 9). This downward trend coincides with the establishment of pines in the catchment, and was estimated to be approximately 350 ML/yr (0.38% of the mean annual flow). However, it is important to note that the GAM analysis demonstrated that the temporal trend is not statistically significant.

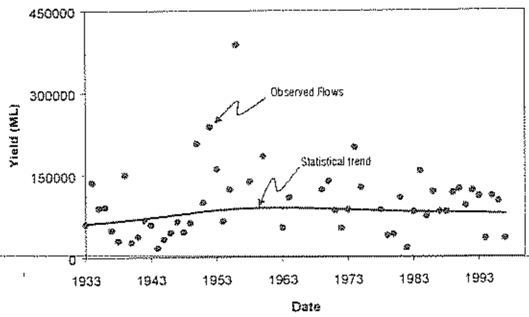

Figure 9. Statistical analysis of streamflow trend for the Adjungbilly catchment.

In large part the landuse changes that have occurred in the Adjungbilly catchment are the conversion of one forest type to another, providing a likely explanation for the relatively small magnitude and statistical insignificance of the observed streamflow trend. This is in contrast to reafforestation of cleared land, in which case the increase in evapotranspiration is much greater.

3.4 Model Simulation

The model was applied to the Adjungbilly catchment over the period 1945 to 1998, for which data was available. A typical logging regime provided by State Forests of New South Wales was assumed for the simulation. The regime allows undisturbed growth of the plantation for the initial fourteen years, following which it is thinned three times. Finally the forest is clear felled when the age reaches 35 years. The logging coupe is then replanted and the cycle repeated.

Despite the trend in streamflow being statistically insignificant, the model was able to satisfactorily simulate the magnitude and nature of the changes in mean annual yield from the catchment (Figure 10).

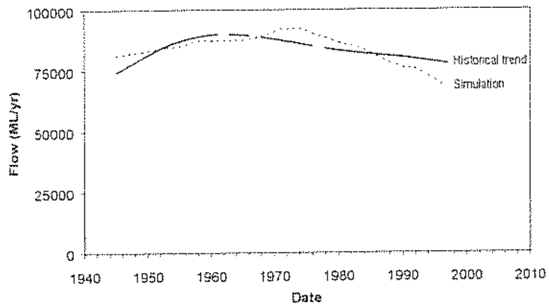

Figure 10. Simulated yield impact for the Adjungbilly catchment.

These model results were obtained directly using the inputs as described in the foregoing sections. No 'calibration' of the model was undertaken. The results thus represent an unbiased application of the empirical evidence in which the model merely incorporates the ability to track changes in yield through time for a spatial mosaic of landuses and forest age under conditions of constant (mean) annual rainfall. Given the complexity of catchment processes and the simplicity of the adopted model, the simulation results for Adjungbilly are surprisingly good.

4. CONCLUSIONS

A numeric model has been developed that simulates average annual changes to catchment yield in response to landuse conversion, natural ageing of forests, and the relative impacts of user defined logging regimes. The model allows characterisation of a study catchment by three broad categories of common landuse – pasture, pine plantation, and eucalypt forest. The functional yield response curves underpinning the model have been developed using statistical analysis of site specific data and current research understanding of forest hydrology. The model is capable of accounting for differences in mean annual rainfall conditions between different study catchments, but does not explicitly account for other spatial variations, such as soil depth or type, for which little information is available.

Despite the complexity in catchment processes and the simplicity of the model, simulation results for the Adjungbilly catchment in southern New South Wales demonstrated that the magnitude and temporal changes in catchment yield could be replicated well.

5. ACKNOWLEDGEMENTS

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