Physically-Based Prediction of Water Yield from Disturbed Forested Water Supply Catchments

Lane, P.N.J[1, 3, 4], P.M Feikema[1, 4], C.B.Sherwin[1], M.C. Peel[2], A. Freebairn[3, 5]

[1]School of Forest and Ecosystem Science, The University of Melbourne, Victoria
[2]Department of Civil and Environmental Engineering, The University of Melbourne, Victoria
[3] eWater Cooperative Research Centre
[4] Cooperative Research Centre for Forestry
[5]CSIRO Land and Water, Canberra, ACT
Email:patrickl@unimelb.edu.au

Keywords: *Macaque, fire, climate change, catchment yield*

EXTENDED ABSTRACT

Disturbance of forested catchments by fire, logging, or other natural or human induced events that alter the evapotranspiration regime may be a substantial threat to domestic, environmental and industrial water supplies. While security of water supplies have always been of high importance in Australia, the recent long-lived drought, climate change predictions and two major “mega fire” events in 4 years that have burnt over 2 million ha of native forest in Victoria alone, have placed alarming uncertainty on the State’s water resources. Furthermore, there are predictions of more frequent and intense wildfire under climate change (Howe *et al.*, 2005). Physically-based models that can predict the hydrologic impact of forest disturbance and climatic inputs will be crucial for understanding changed water yields and for informing forest management options. One such model is Macaque (Watson, 1999), a physically based spatially distributed daily time step process model that was developed specifically to replicate the water yield variation over time observed in Victorian central highland catchments after the 1939 bushfires. This paper describes the modelling of the long term changes in water yield from two fire affected catchments, and of fire and climate change scenarios in Melbourne’s principal water supply catchment (488km^2). The effect of scale, data availability and quality, and of species parameterisation is explored.

For the two fire affected catchments, Mitta Mitta (1533 km^2) and Tambo (551 km^2) 250 year simulations were run with the changed vegetation conditions and with no disturbance. Macaque predicted a significant yield decrease, with a maximum annual change of 17% for the Mitta Mitta and a long-term decrease of 7%. These values were 20% and 7% for the Tambo. However there were some important uncertainties identified. The model calibrations although reasonable (Nash & Sutcliffe (E) = 0.5-0.6) demonstrated there were periods with significant discrepancies between observed and predicted flows in the calibration phase. It is likely that poor precipitation coverage over large, sparsely populated catchments is one cause. A second may have been the use of the model outside of its development range; i.e. into areas with drier forest types where the evapotranspiration characteristics are not well known.

Subsequently, Macaque was calibrated for the Thomson catchment (488 km^2), which has a better coverage of rainfall stations, and a far smaller proportion of drier eucalypt species. The calibrations were much improved (E = 0.7-0.8), demonstrating Macaque to be an appropriate model for evaluating forest disturbance where input data is of high quality. Simulations of fire scenarios and of potential climate change scenarios were run. The latter were based on CSIRO projections of rainfall and temperature changes for the Melbourne region. There was no consideration of vegetation physiological responses to climate change. The simulations give an indication of the magnitude of yield responses that should be considered by catchment managers. Such predictions can be placed in the context of other disturbances or management decisions such as timber harvesting. The ability of Macaque to simulate spatially-distributed disturbance is important.

The modelling has produced useful insights into potential yield responses to plausible disturbance scenarios. The research also demonstrates the decline in model performance when input parameters are problematic.

1. INTRODUCTION

In Australia, and many other countries, forested catchments yield most of the water for domestic, agricultural, industrial and environmental uses. For example, the water supply for Melbourne's over 3 million people is derived almost entirely from native forest catchments. Disturbance of forested catchments by fire, logging, or other natural or human induced events that alter the evapotranspiration regime may be a substantial threat to water supplies. Whilst security of water supplies have always been of high importance in Australia, the recent long lived drought, climate change predictions and two major "mega fire" events in 4 years that have burnt over 2 million ha of native forest in Victoria alone, have placed alarming uncertainty on the state's water resources. Melbourne has now experienced a run of 11 years of below long term median annual rainfall, which represents a statistically unusual event estimated to have a recurrence of 1:1000 years (M.Peel, pers comm.).

The net result of these events and threats is that many existing forecasts of both short- and long-term yields may be redundant. Models are required that can handle spatially variable disturbances at the appropriate spatial scale. These scales may be up to 10^3 km^2. There is also a need to represent forest growth dynamics as the temporal response of some eucalypt forests is known to be highly variable.

The wildfire events of 2003 and 2006-07 in south eastern Australia have imposed a major level of disturbance on forested catchments. The 2003 event was the catalyst for a hydrologic analysis of both water yield and water quality from Victoria's catchments at a range of scales. One model used for prediction of long-term yields was the Macaque forest yield model, developed by Watson (1999). Two catchments were modelled to assess the impact on yield as a function of the fire severity, areal extent, and species responses. Subsequent work with Macaque has focused on further disturbance scenarios in Melbourne's water supply catchments, including fire, logging and climate change.

1.1. Model description

The Macaque model was originally developed by Watson (1999), with summaries given by Watson *et al.* (1999, 2001) and Peel *et al.* (2000 ,2001). It was originally developed using the Tarsier framework and was written in C++. Recently it has been ported/translated into C# .NET using TIME (The Invisible Modelling Environment; Rahman et al., 2004). The major features developed for the first release of Macaque as a Cooperative Research Centre for Catchment Hydrology Toolkit product included a "Configuration Wizard" (a number of pages for gathering data, defining catchment boundaries and setting parameters), a main screen for visualisation of data, a data base persistence layer for storing and retrieving configurations, the ability to run different configurations, the ability to select and record whole of catchment variables, a number of statistical tools (bivariate and univariate statistics) for manual calibration, and a screen for changing model parameters.

Macaque is a physically-based model. Wherever possible, model parameters are assigned values based on direct measurements of physical properties within the respective catchment, or reasonable and appropriate values taken from the literature. A few parameters, particularly those relating to soil properties, remain for calibration against observed water yield. Such parameters are unlikely to change with forest disturbance. Once they are calibrated for a given catchment under known disturbance regimes, they are considered to be robust. Therefore, model predictions are considered to be valid when future disturbance regimes are simulated.

The catchment is discretised spatially into hillslopes then into smaller areas known as elementary spatial units (ESUs). Each ESU is modelled separately, and individual ESUs are linked together by subsurface water flow pathways within a hillslope. Within each ESU, two layers of vegetation are represented: canopy and understorey. Precipitation interception and throughfall is modeled for both these layers. Solar radiation is also propagated through, and absorbed by these layers. The Penman-Monteith equation is used in the model to calculate evapotranspiration (ET) from each of the vegetation layers, as well as to calculate evaporation from the soil. The Van Genuchten model is used to calculate recharge from the unsaturated to the saturated zone. Darcy's Law is used to move saturated water laterally within hillslopes using explicit transfers of water between neighbouring ESUs.

A detailed climate sub-model is used to convert precipitation and temperature range inputs into required climate variables such as radiation and humidity for the estimation of evapotranspiration. Spatial changes in climate, vegetation, soil, and topography cause changes in water yield. Changes in forest type and age are represented by changes in leaf area index (LAI) and leaf conductance to water vapour (e.g. Figs. 1 and 2). These are specified to the model as a series of LAI with age and conductance with age curves for each forest type (e.g. Alpine Ash, Mixed Species, Rainforest, Heath).

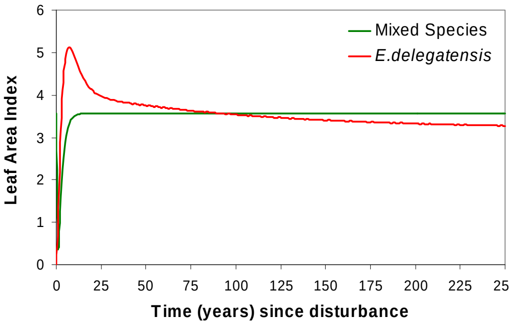

Figure 1. Leaf area index –age relationships for *E. delegatensis*

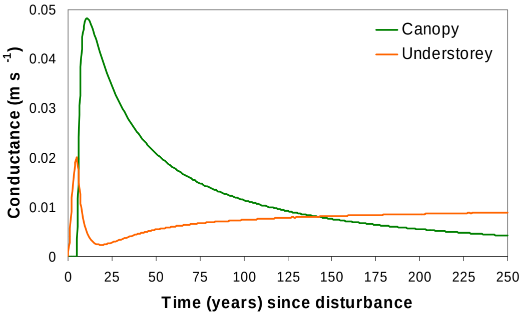

Figure 2. Conductance-age relationship for *E.delegatensis* stand over- and understorey

1.2. Data requirements

(i) Topographic - a digital elevation model (DEM) is required for discretisation of the catchment. A 20 m DEM derived from the Victorian Corporate Geospatial Data Library was used.

(ii) Vegetation – layers of species type and age, mapped by the Victorian State Forest Resource Inventory (Fig. 3) that represent the known disturbance history. The number of layers required depends on the number of times the vegetation in a particular grid cell has been disturbed. Typically there are 3-4 species age maps required. Plus the curves for the temporal distribution of leaf area index (LAI) and canopy conductance for each species (Figs. 1 and 2). Both overstorey and understorey components are represented.

(iii) Climate inputs – daily time series of maximum and minimum temperature and precipitation. A precipitation surface is derived from multiple linear regression analysis of monthly precipitation from stations in or near the catchment against a set of base precipitation stations. The regression analysis terms are then spatially interpolated and the daily surface precipitation is driven by the base stations with continuous records (Peel *et al.*, 2000). Observed temperature data is used to estimate lapse rates for distributing temperature to each ESU. Thirteen rainfall stations were available for the Mitta Mitta, and 10 for the Tambo. Three temperature stations were available for both catchments.

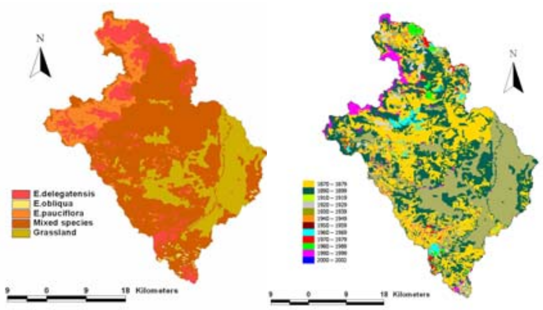

Figure 3 Species and age maps for Mitta Mitta catchment.

1.3. Modelling procedure – calibration

Macaque was used to model the actual 2003 fire impacts for the Mitta Mitta River at Hinnomunjie (1533 km^2) and Tambo River at Bindi (551 km^2) catchments, located in north east Victoria. The model was calibrated against observed streamflow for the available period of streamflow record up to 2002. The model was calibrated to maximise the Nash and Sutcliffe (1970) coefficient of efficiency (E), and to minimise the % difference in the mean (μ), standard deviation (SD) and coefficient of variation (CV) between observed and predicted monthly flow. The K-fold cross validation method described by Efron and Tibshirani (1993) was used to cross validate the calibrated models, resulting in 3 cross validated periods. That is, the flow record is split into thirds, and 2 of the thirds calibrated and the other used for validation. The column headings in Tables 1-3 refer to the first (1) second (2) or third (3) third. For example, C 2_3 refers to the calibration parameters for the second and third third, V 1 is the corresponding first third used for validation in this case. C_A is calibration against all observed monthly flows. E values of 0.6 are regarded as satisfactory and 0.8 as good (Chiew et al., 1993).

An additional check on the model performance is through the construction of flow durations curves (FDCs), so that the distribution of flows can be evaluated. Although there are a number of parameters available for calibration, we followed the example of Peel et al. (2001) who concentrated on two parameters: the precipitation scalar and the ratio of the hydraulic gradient to the surface gradient. We also varied the lapse rate and soil hydraulic conductivity and depth, but found the latter two parameters to be insensitive. The calibration results are given in Tables 1 and 2.

Table 1. Calibration results for Mitta Mitta

	C 1_2	V_3	C 2_3	V_1	C 1_3	V_2	C_A
E	0.5	0.5	0.6	0.5	0.5	0.6	0.6
% μ	-3.8	10.0	6.0	-9.1	0.8	1.1	0.9
% SD	-2.1	-1.2	-0.4	-6.1	-2.9	0.3	-1.6
% Cv	1.8	-10.3	-5.6	3.3	-3.7	-0.8	-2.5

Table 2. Calibration results for the Tambo

	C 1_2	V_3	C 2_3	V_1	C 1_3	V_2	C_A
E	0.4	0.6	0.4	0.5	0.5	0.3	0.4
% μ	-9.0	-9.9	-11.5	-4.9	-7.1	-12.8	-9.3
% SD	-0.6	-7.5	6.1	-12.8	-11.0	12.8	-1.8
% Cv	9.3	2.6	19.9	-8.3	-4.2	29.4	8.2

The calibrations were reasonable for the Mitta Mitta, with good agreement on total flows, little difference between CV of predicted and observed monthly streamflow, and low percentage variation from the observed mean for predicted monthly flows. The FDCs also showed good agreement for the high and median percentiles, but were a poorer fit for low flows, Macaque slightly underestimating high flows and overestimating low flows. The E values of around 0.6 show that although the model was adequate, there were periods where the model could not mimic the observed flow. Most notable are several periods where the modelled flow is either significantly lower than the observed, or does not respond at all. It is most likely this is a function of poorly charactersied precipitation inputs as the model produces reasonable responses to precipitation for the majority of the calibration. The E value rises if these periods are not considered. A significant problem in modelling a large catchment that is sparsely populated is obtaining high quality continuous precipitation coverage that encompasses the range of rainfall gradients, particularly where there are significant elevation differences. The calibration for the Tambo was more problematic. Optimising the calibration parameters proved difficult, particularly in maximising E while retaining good flow statistics.

1.4. Simulation of fire impacts

An additional vegetation disturbance layer was produced, based on fire severity mapping. There were a number of issues to be resolved. The most important was related to the ecological response of eucalypts to fire. This response is not uniform, but is crucial hydrologically. For some species such as *Eucalyptus delegatensis, E. regnans* and *E. nitens* fire is the ecological driver. Trees die if exposed to even moderate fire and they regenerate in high density even ages stands which have been shown to use more water than older stands (Kuczera, 1987; Vertessy et al., 2001). The mixed-species response is less certain as they are resistant to fire unless very severely burnt. A key issue was the assignation of the mixed-species eucalypts to either recovered or regrowth categories. Following some qualitative analysis of remotely sensed recovery data, all mixed-species stands within Class 1 severely (crown burnt) and 60% in Class 2 (severe crown scorch) were considered to be regrowth stands. All *E. delegatensis* stands exposed to Class 1 and 2 were deemed to be dead (Fig 4).

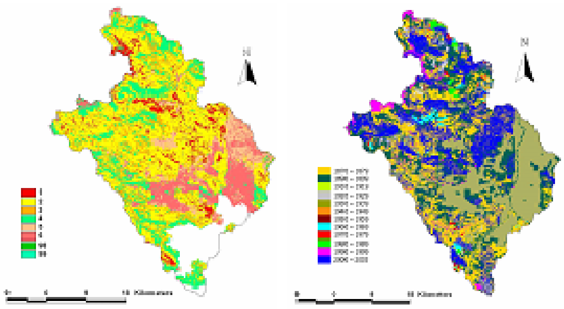

Figure 4. Maps of fire severity classes and resultant age distribution

Table 4. Percentage area and species modelled as regrowth forest

Catchment	Species				
	E.delegatensis	Mixed	*E.pauciflora*	*Other*	Total
Mitta Mitta (%)	5.20	20.90	5.02	0.11	31.24
Tambo (%)	3.88	32.35	0.05	0.00	36.28

The long-term fire impact was modelled by running a No-Fire and a Fire scenario from 2003 until 2254. A constant climate was imposed by repeating the precipitation and temperature from a single year for the 300 (250 years post 2003) year sequence. The climate data were selected from the calibration period as the year in which the three climate base stations were all closest to the calibration period average. This single-year sequence means the modelled water balances are purely a function of vegetation. However it masks any impact of inter-annual variability.

2. RESULTS

Fig 5 is the predicted yield for Fire and No-Fire scenarios for the Mitta Mitta. The maximum decrease in yield, reached in 2014, was 17% relative to the no-fire predicted yield. A 41% increase is predicted for the immediate post-fire year, declining rapidly to no-fire levels by 2006. The cumulative predicted decrease in yield is 10965 GL over the 250 year scenario, which is a

7% decrease overall. A notable aspect of the simulated yield is the increasing yield from the No Fire scenario. This is due to the decline in LAI and conductance as the forest ages. Interestingly, by 2055 the fire curve equals the No-Fire yield at 2003. Subject to no other major disturbances, there would be an increase in yield relative to pre-fire levels over the whole simulation period, although a positive cumulative difference in yield would not occur until 2103.

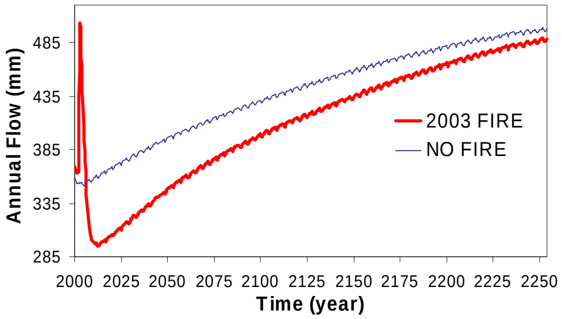

Figure 5. Predicted long-term flow for Fire and No Fire scenarios for the Mitta Mitta catchment

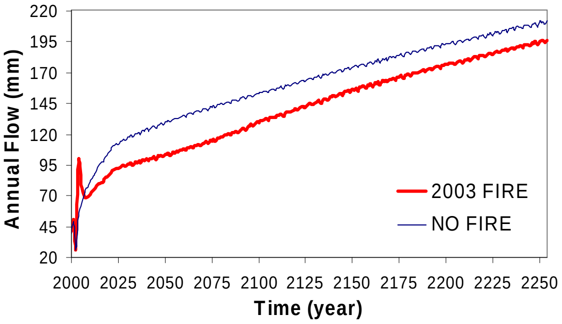

Figure 6. Predicted long-term flow for Fire and No Fire scenarios for the Tambo catchment.

The predicted response from the Tambo at Bindi (Fig. 6) is greater than for the Mitta Mitta. The peak decrease is 20%, while the change over the full 250 year series is 7%. The difference between the two catchments may be partly explained by the larger proportion of the catchment assigned regrowth forest in the Tambo. There is also the possibility that the calibrated parameters are unable to adequately represent the system, and the model is over sensitive to the scale of disturbance.

2.1. Model performance

The calibrations for both catchments result in some significant uncertainty around the predictions. An exploration of possible causes is warranted. As mentioned above, it is highly likely that precipitation inputs are less than desirable. Another potential issue is the species that are modelled. Watson (1999) parameterised the model with LAI-conductance-age data collected from experimental catchments in the Victorian Central Highlands. Although some of the mixed-species eucalypts are common to both the Watson (1999) catchments and those modelled for fire impacts, there are a number of other eucalypt that are found in the drier areas of the Mitta Mitta and Tambo. They are unlikely to have the same LAI-conductance-age relationship as the mixed-species in wetter environments. Alternatively, there is a possibility that Macaque cannot be applied outside of the areas used for its development.

To further evaluate the model performance a catchment with better precipitation coverage can be used. The Thomson catchment (488 km^2) is Melbourne's most important water supply catchment. There were 62 rainfall stations within or near the catchment that could be used to produce a rainfall surface. The calibration of the Thomson returned the calibration statistics given in Table 3.

Table 3. Calibration results for the Thomson catchment

	C 1_2	V_3	C 2_3	V_1	C 1_3	V_2	C_A
E	0.8	0.8	0.8	0.8	0.8	0.7	0.8
% μ	0.6	-12.0	-5.3	-0.5	-6.2	1.8	-3.6
% SD	6.2	-11.5	-0.5	3.7	-2.3	9.5	1.3
% Cv	5.5	0.7	5.1	4.2	4.1	7.5	5.1

These calibration results suggest Macaque can be used to explore disturbance scenarios with some confidence where the input data is of reasonable quality. Further, the species mix is less varied than found in the Mitta Mitta and Tambo catchments. There is a greater proportion of *E. regnans* and *E. delegatensis* which have the best hydrologic characterisation, and the mixed-species eucalypts are in higher rainfall areas than much of the Mitta Mitta. They are more likely to conform to the default LAI-conductance-age relationships.

A further set of simulations to explore fire and climate change scenarios for the Thomson were run as part of a study on potential threats to Melbourne's water supply. For the fire simulations, a range of "mortality" events in different parts of the catchments, and with varying combinations of species, were imposed. The scenarios were based on mortalities from the 1939 fire event. As for the 2003 fire scenarios, a single year representative climate was used for the 250 year runs. In contrast to those simulations, all vegetation ages were set to zero to evaluate the relative impact for the entire age sequence. The results are given in Fig. 7. Additionally, multiple events were simulated, using the 1939 fire event scenario (Fig. 8). The 100% and