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Large Scale, Long Term, Physically Based Prediction of Water Yield in Forested Catchments

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Abstract A water balance model was used to simulate the long term increases in water yield with forest age observed in Victoria's Ash forests and characterised by the Kuczera curve. Specifically, the hypothesis was tested that water yield changes could be explained by changes in evapotranspiration (ET) resulting from changes in leaf area index (LAI). A curve predicting changes in the *total* LAI of Mountain Ash forest was constructed based on ground based Li-Cor plant canopy analyser (PCA) observations and their correlation with Landsat Thematic Mapper (TM) measurements of the transformed normalised difference vegetation index (TNDVI). A further curve for Mountain Ash *canopy* LAI was constructed, based on destructive LAI measurements and stem diameter measurements. The large scale, physically based water balance model Macaque was used to evaluate the effect of changes in LAI on predicted streamflow over an 82 year period spanning the extensive 1939 wildfires. The use of the LAI curves induced a positive change in the predicted hydrographs relative to the case for constant LAI, but the change was not large enough. Predicted water yield from older forests was not as high as that observed. Of a number of possibilities, concomitant changes in leaf conductance were suggested as an additional control on streamflow. These were estimated using data on stand sapwood area per unit leaf area and coded into the model. The hydrograph predicted using both the LAI curves and a new leaf conductance versus age curve accurately predicted the observed long term changes in water yield. Effectively, the Kuczera curve was able to be reproduced. We conclude that LAI is a partial control on long term yield changes, but that another 'water use efficiency per unit LAI' control is also operative, most likely associated with declining leaf conductance with forest age.

1. INTRODUCTION

In the forested catchments that supply water to Melbourne, an important relationship between water yield and forest age is observed. Yield is lower from regrowth forests (*c*. 10-100 years old) than from mature and old-growth forests (> 100 years old). The effect of logging and wildfire within these catchments is to reduce their age and consequently their water yield. A *wood versus water* trade-off results, having significant economic implications for the forests' managers, Melbourne Water and the Victorian Department of Natural Resources and Environment (DNRE) (Read Sturgess and Associates, 1992).

The yield/age relationship has been quantified by Kuczera (1985, 1987) for the Mountain Ash (*Eucalyptus regnans*) forests which dominate the catchments using what has become known as the 'Kuczera curve' (Figure 1). Starting from 2 years after age zero, the curve predicts a rapid decline in yield to age 27, and then a gradual rise back to 'equilibrium' levels by about age 200.

A body of evidence has grown suggesting that concomitant changes in forest leaf area index (LAI) with age are responsible for the yield/age relationship. This is shown through the dependence on LAI of interception and transpiration, both of which reduce the water yield (see review by Vertessy et al., 1994a).

The Kuczera curve is used operationally by DNRE in the management of the Thomson catchment with regard to the locating of new logging coupes. The curve is used to predict the effects of planned forestry operations. However, the same curve is used for all Ash type forests regardless of other environmental influences on water yield such as precipitation and radiation. Precipitation has a range of well over 1000 mm within Mountain Ash

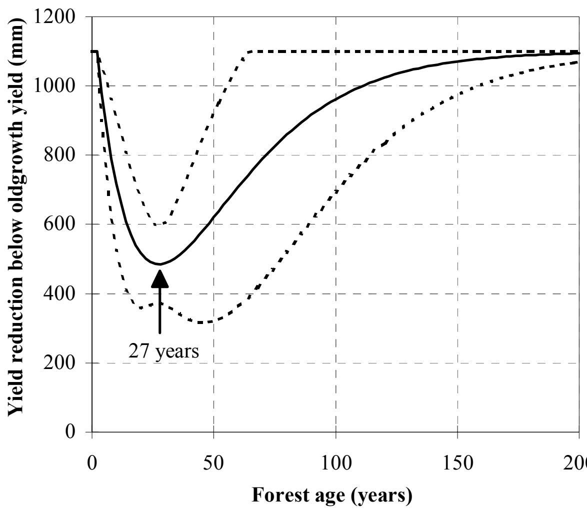

Figure 1: The Kuczera curve (with 90% confidence limits) predicting water yield decline from forest age in Mountain Ash forests.

forests, and radiation varies greatly between north and south facing slopes. We suggest that current practice is limited by inaccuracy in water yield prediction resulting from the assumption of spatial invariance of the yield/age relationship. Ash forest management could be improved by allowing for large scale, spatially variable responses of hydrology to forestry operations.

In this paper, we attempt to model the Kuczera curve using a large scale physically based water balance simulation model. This will lead the way to better forest management through such outcomes as a range of yield/age curves sensitive to the large scale heterogeneity of physical parameters observed within Melbourne's water supply catchments.

2. STUDY AREA

The study area is the Watts, Grace Burn, and Coranderrk catchments (total area 145 km^2) of the Maroondah catchment group about 60 km north east of Melbourne. The area is mountainous and forested mainly with Mountain Ash (59%) and other eucalypts. Mean annual precipitation ranges from 1100 mm to 2800 mm. Most of the forest was burnt and completely regenerated in 1939. Prior to this date, predominantly old-growth (>100 years) forest is likely to have been present (Kuczera, 1985).

3. HYPOTHESIS

The operation of the model is described below. Initially, however, we concern ourselves with the hypothesis that will enable the model to simulate the Kuczera curve:

The relation between water yield and forest age is determined by a concomitant relation between LAI and forest age through the control of evapotranspiration by LAI.

To test this hypothesis, we first search for relationships between LAI and age.

4. TOTAL LAI VERSUS FOREST AGE

Both total LAI and canopy LAI are investigated, the former first. A curve relating total LAI to forest age was formed using above and below-canopy remote sensing data as follows:

4.1 Li-Cor PCA estimation of total LAI

A Li-Cor LAI-2000 Plant Canopy Analyser (PCA) (Welles and Norman, 1991) has been used extensively by various workers in the Ash forest. The PCA compares light above the vegetation with that below to estimate the area of the leaves intercepting the light. LAI estimates made by the unit have been validated against destructive measurements of LAI by Vertessy et al. (1994b). The unit measures LAI above the instrument height and so excludes the LAI of the ground cover. It also includes the area of stems and branches which, for simplicity, is here assumed to cancel the excluded LAI of ground cover.

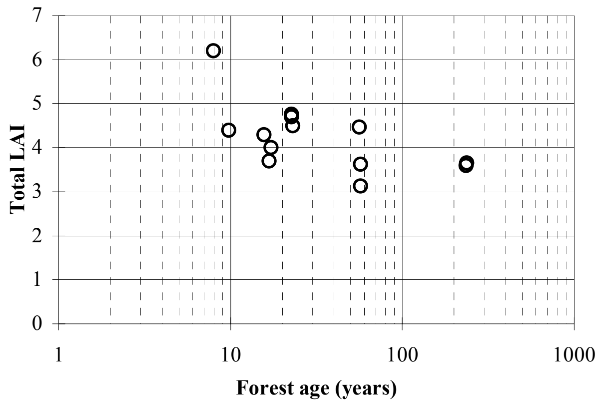

Figure 2: Total LAI measured using a Li-Cor PCA plotted against forest age.

Figure 2 summarises all the PCA data which were available. Each point in the Figure represents between 25 and 1650 individual LAI measurements (total: 4616). Figure 2 indicates that total LAI, which is zero at age zero, rises to a peak of over 6 at about 8 years and then gradually declines to just above 3 at over 200 years of age.

4.2 Satellite remote sensing estimation of total LAI

Four Landsat-5 Thematic Mapper (TM) images from different years ('90, '91, '93, '94) were obtained for the study area. These were radiometrically corrected, shading corrected, gamma corrected, and contrast stretched for optimum visualisation of forest features. The most obvious features in the imagery were the logging coupes near the study area. The regeneration of these could easily be discerned from the sequence of images. The estimation of LAI using the imagery was based around this observation.

Sampling areas were defined from logging coupes and broad-scale mapped forest-types as follows. Logging maps and dates for the forest blocks adjacent to the study area were obtained from DNRE. Twenty-six logging coupes of varying ages were selected for analysis. Also from DNRE, digital maps of canopy species and origin date were obtained for the study area. This resulted in a total of 66 sampling areas varying in age from zero to 235 years.

Following Lacaze (1996), the transformed normalised difference vegetation index (TNDVI) was selected as a potential estimator of LAI. The TNDVI is a non-linear re-scaling of the commonly used NDVI between values representing infinite vegetation and background levels (i.e. bare earth). Mean TNDVI was calculated for each sampling area in each image and calibrated such that

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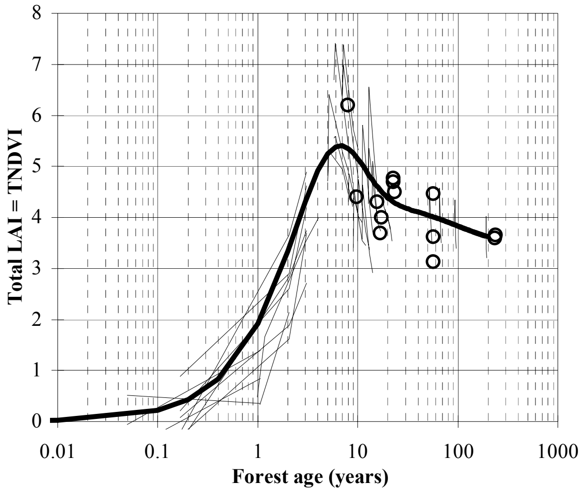

Figure 3: The patterns of LAI variation with forest age estimated from a matching of Landsat TM TNDVI data and PCA data.

TNDVI equalled LAI with minimal error.

Figure 3 shows the results of this process. The numerous short lines are four year series of TNDVI values from each sampling area. The circles are the PCA estimates of LAI from Figure 2. The continuous line is a curve of similar mathematical form to the Kuczera curve which was fitted by eye to the LAI and TNDVI data. The TNDVI data are shown to be good predictors of LAI for two reasons. Firstly, for ages younger than 8 years, the data consistently follow the mandatory pattern from zero at age zero to some larger value by the time dense vegetation is established at about 5 years. Secondly, the TNDVI data beyond 8 years follow the pattern of the PCA data with a rapid then gradual decline from 8 years to over 200 years. Note that this correlation does not necessarily prove that LAI *itself* (as opposed to a useful proxy) is being measured by satellite.

5. CANOPY LAI VERSUS FOREST AGE

The forest canopy is a stronger control of evapotranspiration (ET) per unit LAI than the understorey due to its better exposure to the sun and the atmosphere. Canopy LAI is thus investigated separately.

Watson and Vertessy (1996) constructed a canopy LAI curve for Mountain Ash from destructive measurements of LAI and allometric models. The procedure is summarised here. The core of the method is a model predicting the leaf area (LA) of an individual tree from both its diameter at breast height (DBH) and the mean DBH of the stand to which it belongs. This model was constructed using a combination of log/log regressions of 78 destructive LA measurements against DBH, and log-log regressions of mean stand LA against mean stand DBH. Auxiliary relations were formed between forest age and stand stocking density, mean stand DBH, and the variance of stand DBH. These relations were mathematically combined with the LA/DBH model to produce an curve predicting LAI from age as plotted in Figure 4. An indication of the curve's accuracy is given by the plotted points which represent destructive measurements of LAI from single plots. The curve itself is based on more data than these points and so is considered to be more accurate than the points. A significant limitation of the curve is that it is undefined for ages 5 and below, when it is set to zero.

The total and canopy LAI curves shown in Figures 3 and 4 respectively were used as input to Macaque, which is described below.

6. THE MACAQUE MODEL

6.1 Description

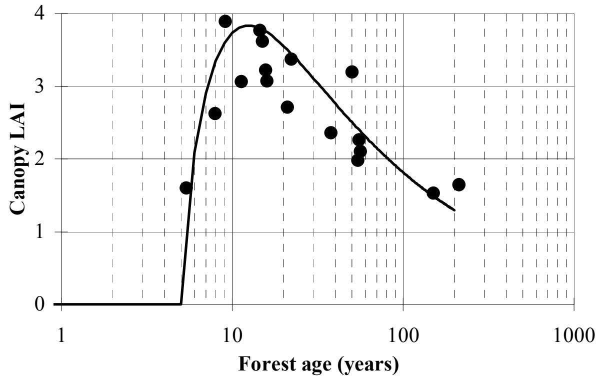

Figure 4: Mountain Ash canopy LAI versus age.

Macaque is a large scale, long term, physically based water balance model which predicts the water yield of forested catchments subject to land cover change. It operates at a daily time step and is designed to simulate water balance during periods of over 100 years for catchments over 100 km^2 dissaggregated into over 1000 elementary spatial units (ESUs). Note that the spatial features of the model are not exploited here but are essential for intended future applications.

Macaque is a distribution function model, operating in a similar way to RHESSys (Band et al., 1993) and TOPMODEL (Beven et al., 1994). Catchments are first divided into a number of hillslopes. Then, a topographic wetness index is calculated for all parts of each hillslope and areas of similar wetness index are grouped together as the ESUs of the model. Lateral flow between ESUs is implemented implicitly using a 'generalised distribution function' at a rate controlled by a 'lateral redistribution factor' (see Watson, 1997; Watson et al., 1997).

Within each ESU, the model implements a three-layer (canopy, understorey, and soil) Penman-Monteith representation of evapotranspiration, with detailed representation of such factors as energy balance, leaf conductance, interception storage, radiation propagation, humidity gradients, and soil water extraction. Much of the vertical structure is based on

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that embodied within Topog (Vertessy et al., 1995) and RHESSys (Band et al., 1993) with some new developments.

The model requires daily precipitation and maximum and minimum temperature at a base station as time series input.

6.2 Initial parameterisation

The first step in the application of the model was the initial quantification of model parameters. As discussed in detail by Watson (1997), emphasis was placed on physical realism, with parameters determined by either direct measurement of physical properties, or calibration against numerous data on *internal* model variables.

Four key *spatial* parameter groups warrant special mention (see Watson et al., 1996, 1997). Topographic parameters (elevation, slope, aspect, wetness index) were determined from a 25x25 metre digital elevation model (DEM) interpolated from digital contour data. Precipitation was distributed by mapping a mean monthly precipitation index (MMPI) using three dimensional spline interpolation. LAI was distributed spatially using a digital forest type map supplied by DNRE in combination with separate LAI/age relations for each mapped species. The curves developed above were modified for species which are morphologically similar to Mountain Ash. Simple climax curves (starting at zero and rapidly rising to a constant climax value) were used for other species. After some failed attempts to map soil properties such as soil depth at large scales, all soil parameters were mapped as being spatially invariant.

6.3 Hydrograph calibration

After realistic internal model operation was attained through measurement and calibration of model parameters against internal data, calibration against outflow hydrographs was undertaken. Chiefly, three years of streamflow data (1982-4) were used. The shape and magnitude of the daily baseflow and stormflow response were able to be manipulated using a small number of otherwise loosely constrained parameters including: a parameter expressing soil depth, the lateral redistribution factor (see above), parameters controlling the rate of baseflow exfiltration, and a parameter expressing the control of leaf conductance by humidity. The calibration process was subjectively judged as being complete when the predicted hydrograph matched the observed hydrograph, concomitant with all internal model variables being within realistic ranges. Quantitative measures of hydrograph accuracy were not used because this would place undue emphasis on the intricacies of streamflow prediction. Most water flux in the study area is atmospheric, not stream discharge.

7. LONG TERM SIMULATION

Long term simulations of water balance and water yield over most of the 20th century were undertaken in order to predict the hydrological effects of the 1939 wildfires and, implicitly, model the Kuczera curve.

7.1 Long term data

Monthly streamflow data were available for the three catchments from 1910 to the present. The records were summed into a single, aggregated streamflow record representing a combined catchment area of 145 km^2. Thrice weekly precipitation data from 1910 to the present were available for a site at Blacks' Spur inside the study area. These were pro-rated to construct a long term daily record using daily data from Warburton post office. Tests revealed that the pro-rated data lead to significantly better hydrograph predictions than raw data from less central sites. Daily maximum and minimum temperature data were taken from the Melbourne Regional Office station of the Bureau of Meteorology. This is the nearest long term record to the study area which spans 1939.

7.2 Results

Note that, whilst annually aggregated results are reported here, our calibration data indicate that monthly and weekly hydrographs are reproduced with similar accuracy (see Watson et al., 1997).

For comparison, a simulation using effectively constant total and canopy LAI (rising from zero to a climax value in the initial few years of growth) was conducted first as shown in Figure 5a (thin solid line). The temporal signals in the predicted and observed hydrographs match well but there are gross absolute errors during various parts of the century. Near the calibration period, the errors are small, but in the period prior to the 1939 fires, when old-growth forests prevailed, the hydrograph is consistently under-predicted. The main problem is thus under-prediction of streamflow for older forests (>50 years).

The hydrograph predicted using the total and canopy LAI curves described above is shown in Figure 5a with a dashed line. As expected, there is more differentiation between young and old aged forests. However, the differences are not great. Only slight improvement is shown for the older forests (pre-1939), and the predictions have worsened for forests aged around 10 years (the time of the peaks in the total and canopy LAI curves).

These results lead us to strongly question the hypothesis that the relation between water yield and forest age is explained by LAI changes. They suggest that other factors must be considered before a complete explanation is possible.

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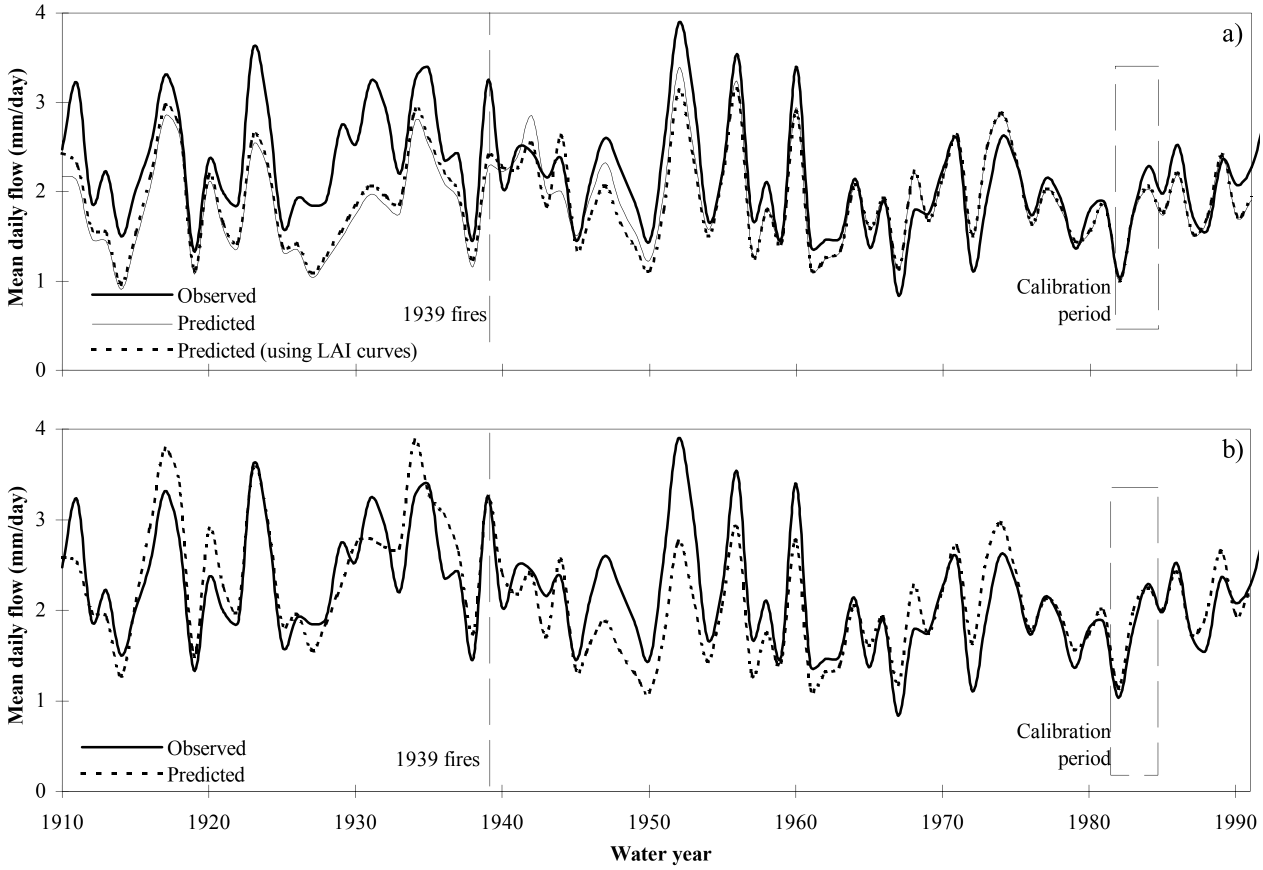

Figure 5: Long term, annually aggregated hydrographs for the Maroondah catchments: a) using constant LAI (thin solid line) and using the LAI curves derived in the text (dashed line); b) using both LAI and conductance curves.

7.3 Interim discussion

The only age-variant parameters of the model, as used in Figure 5a, are total and canopy LAI. There are a number of possibilities as to why LAI changes do not fully explain the observed age/yield relation:

i. Leaf conductance may decline with age. This is discussed below.
ii. Currently, canopy and understorey leaf conductance are modelled as being identical. However, canopy leaf conductance may be greater than understorey leaf conductance, and because canopy LAI declines faster than total LAI (see Figures 3 and 4), this would manifest as a greater decline in transpiration with age. This has not yet been tested.
iii. Non-Ash type forests may exhibit LAI decline as well as Ash type species. This is likely to be the case, although unlikely to induce the required hydrograph changes because the water yield from, and area covered by these drier forests is small.
iv. The aerodynamic resistance, particularly between the understorey air and that above the canopy, may increase as the forest increases in height. Preliminary calculations indicate this increase is insufficient to reduce ET by the necessary amount.
v. The precipitation and/or streamflow records may contain erroneous trends. We have tested these possibilities using double mass curves and associated analyses. Apart from the known bias in the Maroondah Dam precipitation record (Kuczera, 1985), which is not used here, there are no major trends in the data.
vi. The model may be wrong.
vii. The LAI curves may be wrong.

8. LEAF CONDUCTANCE RELATIONS

Possibility (i) above was investigated further:

Analysis of existing Mountain Ash physiological data revealed that the ratio of stand sapwood area to stand leaf area declines with age (Figure 6). This decline can be interpreted as a reduction in leaf conductance with age, which in turn may be caused by slower leaf replacement in old forests and hence a greater abundance of older, gummed up leaves; or by increased water stress in the leaves of taller, older forests.

The model was modified so that both canopy and understorey leaf conductance were scaled using the relation plotted in Figure 6. Figure 5b shows the resulting simulation. A significant improvement in the hydrograph for older forests is evident. Whilst still under-predicting streamflow for 5-15 year old forest, the model is now able to reproduce the long term changes in water yield with forest age and so effectively reproduce the Kuczera curve.

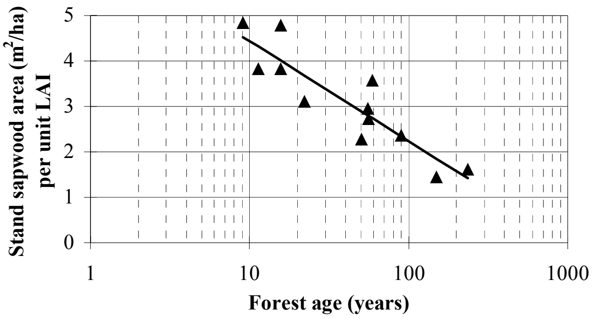

Figure 6: Stand sapwood are per unit leaf area, with power function fitted by linear regression.

9. CONCLUSION

The hypothesis that LAI controls long term water yield changes is strongly questioned. At least one other control appears to be operative, associated with the water use efficiency of trees per unit LAI. Preliminary investigation suggests that declining leaf conductance with forest age is a stronger control on water yield than LAI when each are varied within acceptable ranges. However, the influence of LAI is likely to be strengthened if different conductance were assigned to canopy and understorey leaves, and hence, further investigation is necessary.

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