Modelling Impacts Of Land Use Change On Low Flows In The North Esk River Using The Macaque Model

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Abstract: The water supply of Launceston, Tasmania is partially provided by a run of the river diversion from the North Esk River. The magnitude of future impacts on the level of summer low flows due to land use and land cover changes in the North Esk catchment are important for planning the reliable provision of Launceston's water supply. The Macaque model was applied to the North Esk catchment and several potential land use change scenarios were modelled. Macaque uses species-dependent physiological relationships to predict changes in long-term water use. Notwithstanding the uncertainty associated with assuming the generality of such relationships, predictions of the effect on water yield of each scenario were made. The scenarios modelled were logging of the entire "tall eucalypt" (TE – modelled as *E. regnans*) forest at 100-year, 50-year and 20-year rotations and logging of the entire TE forest plus conversion of all pasture to *E. nitens* plantation on a 20-year rotation. These simulations represent worse case scenarios as the entire TE forest is unlikely to be logged and all pasture is unlikely to be converted to plantation. Simulation of the effects of logging the entire TE forest on a 100-year rotation was found to have little impact on low flows. Logging the entire TE forest on 50 and 20-year rotations reduced low flows by about 20%. Logging the entire TE forest and converting all pasture to plantations on a 20-year rotation reduced low flows by about 25%. The proportion of streamflow sourced from the different catchment vegetation types was analysed and found that 29% of summer low flows were sourced from the TE forest and 4 % from pasture. Thus only 33% of the summer low flows were being modified in the simulated logging rotations. In the case of the North Esk catchment, mountainous regions provide a high proportion of summer low flows that remain unaffected by, and thus limit the impact of, the simulated land use changes.

Keywords: *Low flows; Land use change; Macaque; Logging rotations; Plantations.*

1. INTRODUCTION

The water supply of the city of Launceston, Tasmania is partially provided by a run of the river diversion from the North Esk River. The level of summer low flows is therefore critically important to the reliable provision of water to Launceston. Future impacts on the level of summer low flows due to potential changes in catchment vegetation age and type are explored in this paper by applying the Macaque model to the North Esk catchment.

The North Esk catchment is covered in a mixture of native forest, private forest and pasture. Some native forest and all private forest comprise ash-type eucalypt species (*E. regnans* or *E. nitens*) that yield more water when older than about 50 to 100 years, or younger than about 2 years. The Kuczera curve was the first concise description of the relationship between water yield and age for ash type eucalypts (Kuczera, 1987). The curve is an empirical relationship derived from water yield and forest age data collected over several decades. Macaque, a recently developed physically based spatial process model, has been largely successful in reproducing the Kuczera curve, for the Maroondah and Thomson catchments in Victoria, Australia, using a combination of topography, climate, vegetation species and vegetation physiology relations.

This paper summarises the results of a project by Peel et al. (2002) in which the impact on summer low flows due to potential changes in the vegetation type and age of the North Esk catchment were modelled using Macaque. The project was initiated and managed by Steve Ratcliffe of the Launceston City Council Infrastructure Assets Division and funded by the Launceston City Council.

2. NORTH ESK CATCHMENT

The North Esk catchment is east of the city of Launceston in northern Tasmania, Australia. The

North Esk River at the Ballroom was the only good quality long-term daily streamflow gauge (20/4/1923 - 19/10/1999, 0.07% estimated and 2.30% missing). The catchment area of the North Esk River at the Ballroom is 367.3 km^2 (36730 ha). Figure 1 shows a 100m x 100m digital elevation model (DEM) of the catchment. The North Esk catchment referred to in the remainder of this paper is defined as the North Esk catchment above the Ballroom gauging station.

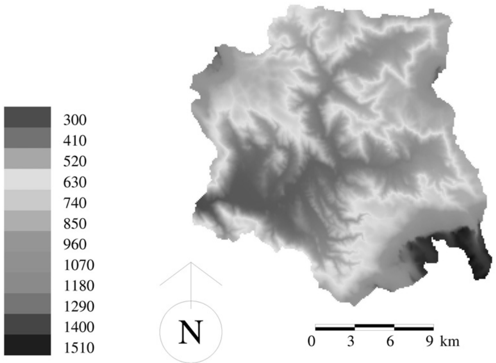

Figure 1. Digital elevation model, in metres (m), of the North Esk at the Ballroom.

The topography of the North Esk catchment is steep and mountainous. Mean annual precipitation ranges across the catchment from 800mm to 2300mm. The catchment has a mixture of land uses, mainly native forest and pasture with some heath, rocky outcrops and plantations. In drier regions, dry sclerophyll species such as Messmate (*E. Obliqua*), Manna (*E. viminalis*) and Swamp Gum (*E. ovata*) are observed. Wet sclerophyll forests are found between 400m and 800m and these predominantly consist of Mountain Ash (*E. regnans*) and Alpine Ash (*E. delegatensis*). At higher elevations Snow Gum (*E. pauciflora*) and Tasmania Snow Gum (*E. coccifera*) are found and above 1200m is generally alpine scrubland (personal communication Pat O'Shaughnessy, 2001). The catchment geology is largely Ordovician mudstone and Devonian granodiorite. Tertiary basalt forms the peaks of Ben Lomond, Ben Nevis and Mount Barrow (McClenaghan & Calver, 1994).

3. MACAQUE

3.1. Model Description

Macaque is a physically based model, meaning that it aims to represent the dominant, real physical processes occurring within a catchment using mathematical equations. This approach is intended to offer predictive capability in situations where measurements of water yield have not been taken, in a way that is sensitive to estimated spatial and temporal changes in climate, topography, and land cover. As much as possible, the many parameters of the model have been given values based on direct measurements of physical properties at Maroondah or on reasonable values taken from the literature. A few parameters, particularly those relating to soil properties, are left 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 specified.

A complete model description is found in Watson (1999), with summaries and improvements described in Watson et al. (1998, 1999 and 2001) and Peel et al. (2002). Relevant features of the model structure and operation are briefly described below.

The model splits catchments spatially into hillslopes, and hillslopes into smaller areas called elementary spatial units (ESUs). Each ESU is modelled separately and these are each linked together by subsurface water flow pathways. Hillslopes are linked together by a stream network, which simply adds up the flow from all the hillslopes to get the total catchment flow. The model runs on a daily time step and requires a daily time series of precipitation and maximum and minimum temperature for input. Predictions of water yield in Macaque are sensitive to climate, plant water use, the amount of water stored within the soil, and the rate at which this water moves into and out of the soil to the streams. Therefore, spatial changes in climate, plants, 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. These are specified to the model as a series of LAI/age and conductance/age curves for each forest type (e.g. Mountain Ash, Mixed Species). Empirical curves for *E. regnans* were developed from observations in the Maroondah group of catchments. The other ash-type species (*E. delegatensis* and *E. nitens*) are assumed to follow the same LAI and leaf conductance patterns as *E. regnans*. Little is known of long-term LAI trends in forests dominated by non-ash species. They are here assumed to have constant LAI, following a rapid initial increase from zero in the first 5 to 10 years following clearing. Whether the ash curves are generally applicable outside Maroondah is unknown.

Following the work of Roberts et al. (2000), a long-term decline in leaf conductance is assumed to hold for all eucalypt forests, including non-ash species. This is a fairly significant assumption, based on limited evidence and further illustrates the importance of research into the long-term growth dynamics of Australia's forests.

3.2. Spatial Data Requirements

Macaque requires spatial information about elevation (DEM, Figure 1), vegetation type, vegetation age, precipitation and temperature.

Maps of vegetation type and age were provided by Forestry Tasmania and for small areas of private forests by Private Forests Tasmania. Peel et al. (2002) details the process by which these maps were modified in order to be compatible with Macaque. The modified vegetation type map is shown in Figure 2. The "tall eucalypt" forest is represented by *E. regnans* and "pasture" by grassland in Macaque.

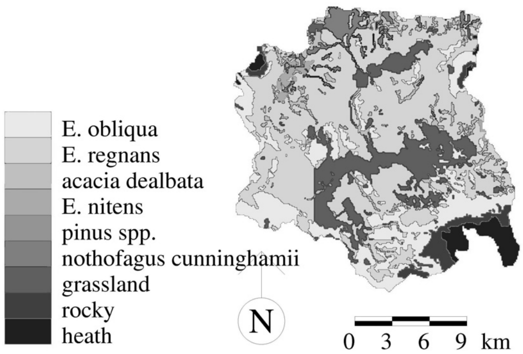

Figure 2. Vegetation type for the North Esk catchment.

Peel et al. (2002) also details the processes by which 42 precipitation and 6 temperature gauges in and around the North Esk catchment were used to estimate daily precipitation and maximum and minimum temperature at each ESU in order for Macaque to run.

4. WATER YIELD IMPACTS OF LOGGING ROTATIONS

4.1. Methodology

Interannual variability of water yield from a catchment is largely influenced by interannual variability of climate but also by changes in vegetation age and type. There are two ways to observe the impact of vegetation changes on long-term water yield when using a model like Macaque. The first methodology is to predict water yield with and without vegetation changes under a future climate of known interannual variability. The difference between water yield predictions is due to the vegetation changes. In this methodology Macaque would be used to model vegetation change scenarios under a range of stochastically generated future climates of fixed interannual variability. This methodology was not pursued due to time and budget constraints. The second methodology, used in this paper, is to predict water yield by modelling vegetation changes under a climate with no interannual variability (Watson, 1999). The predicted water yield is then compared to the water yield from a reference period and the difference is due to the vegetation changes. The appropriate reference period depends on the construction of the climate without interannual variability. In this paper the climate without interannual variability was created by repeating daily precipitation and temperature data from a year closest to the annual precipitation and temperature average (1962) for the number of years required. Thus the observed average or 1962 water yields are appropriate references.

4.2. Calibration and Verification

The Macaque model was applied to the North Esk catchment using a daily time step and calibrated against daily streamflow data. The calibration was optimised by hand using daily summary statistics and the coefficient of efficiency (*E*) (Nash & Sutcliffe, 1970).

The modelling objective was to achieve a percentage difference in mean, standard deviation and coefficient of variation between the observed and predicted daily streamflow of less than 1%. The *E* was also calculated from monthly data to provide insight into the quality of the model fit.

Results of the model calibration (1/1/1950 – 31/12/1969) and verification (1/1/1970 – 31/12/1998) are provided in Table 1.

Table 1 Calibration and verification results for North Esk catchment. Percentage difference between observed and modelled mean (% Mean), standard deviation (% StDev) and coefficient of variation (% Cv).

	E	% Mean	% StDev	% C_v
Calibration	0.84	-0.28	-0.34	-0.06
Verification	0.74	-25.35	-26.07	-0.97

The calibration summary statistics and *E* value indicate that Macaque is replicating the North Esk streamflow acceptably. A further test of how well

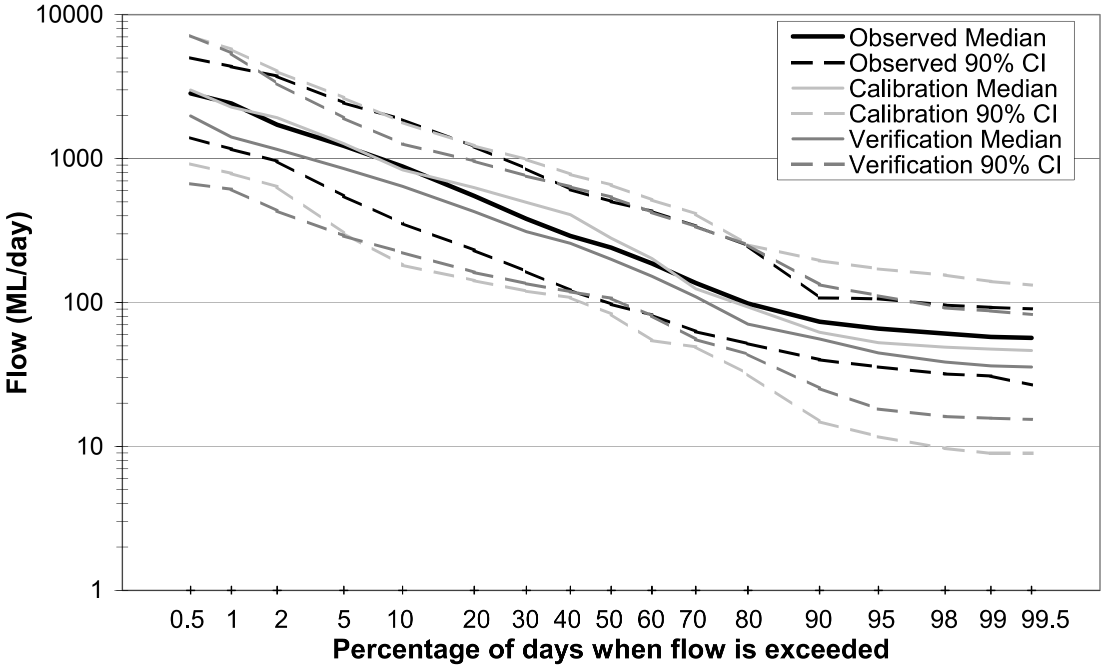

Figure 3. Observed (1/1/1950 – 31/12/1998) and modelled runoff for the calibration (1/1/1950 – 31/12/1969) and verification (1/1/1970 – 31/12/1998) period's median annual flow duration curves, with 90% confidence intervals.

Macaque performs is to look at the summary statistics and *E* value when the model is run on the verification (non-calibration) period of record. It can be seen from Table 1 that the model performance is worse for the verification period. In particular the daily mean and standard deviation are predicted to be about 25% less than the observed.

An analysis of daily mean precipitation, modelled and observed runoff for the calibration and verification periods (not shown) reveals that the mean daily precipitation was 12% less in the verification period than the calibration period. The calibrated Macaque predicts mean daily runoff of 28% less in the verification period than the calibration period. The observed mean daily runoff is only 4% less between verification and calibration periods. An observed reduction in mean daily runoff of only 4% when mean daily precipitation is reduced by 12% over the same period is unusual and may indicate changes to catchment vegetation type or age. Another potential explanation is that Macaque did not capture changes in the spatial rainfall pattern between the calibration and verification periods.

Another check of whether Macaque is adequately representing the rainfall-runoff processes in the North Esk catchment is to compare observed and modelled flow duration curves (FDCs). The method of Vogel and Fennessey (1994) is used to objectively assess whether the modelled FDCs are statistically similar to the observed FDC. Vogel and Fennessey (1994) noted that a method for estimating confidence intervals for a whole of record FDC does not presently exist. They instead recommend constructing a series of daily FDCs for each complete year of record and then estimating confidence intervals for each quantile of the median annual FDC. Insufficient complete years were available in the calibration period, so the calibration and verification periods were combined to form an observed FDC.

In Figure 3 the modelled calibration median annual FDC has a very similar shape to the observed median annual FDC. This indicates that Macaque is representing rainfall-runoff relationships in the catchment very well. The modelled low flows are slightly under estimated compared to the observed flows (on average 12% less for the lowest 40% of flows). The modelled calibration 90% confidence interval is wider than the observed confidence interval since the calibration confidence interval is based on one third less data (20 versus 33 years). The modelled verification median annual FDC (also Figure 3) is largely similar in shape to the calibration and observed median annual FDCs, although vertically displaced by the under prediction of runoff mentioned previously.

4.3. Simulation Results

Macaque was run to assess the impact on water yield of four logging rotation scenarios:

1) The *E. regnans* forest is logged and replanted on a 100-year rotation.
2) The *E. regnans* forest is logged and replanted on a 50-year rotation.
3) The *E. regnans* forest is logged and replanted on a 20-year rotation.

4) The *E. regnans* forest is logged and replanted on a 20-year rotation and pasture is converted to tree farms, logged and replanted on a 20-year rotation.

Each scenario was run for 2 rotations. In the first rotation, pre-existing (often mature) forest or pasture is replaced by *E. regnans* (in the case of forest) or *E. nitens* (in the case of tree farming). In the second rotation the regrowth is logged and replanted. The first rotation models the water yield impact of the introduction of a logging rotation policy, while the second rotation models the long-term water yield impact once a logging rotation is established.

The scenarios modelled are worst-case scenarios since all forest of a particular type are available for logging in Macaque. In reality, codes of forest practice require buffer strips around streams, etc, so the entire forest is not available for logging. Likewise all pasture is unlikely to be converted into tree farms.

In each scenario the interaction between climate and the spatial pattern of vegetation changes within the catchment results in differing water yield impacts each year. Thus median annual FDCs are ideal for comparison of the average impact on water yield. The observed median annual FDC is used as the reference against which the scenario median annual FDCs are compared.

A summary of the impact on mean daily flow and the lowest 40% of flows (from median annual FDCs) is provided in Table 2 for all scenarios. The percentage difference between modelled calibration flow and observed flow are also presented in Table 2 since there are small errors in the way Macaque models the North Esk catchment (as demonstrated in the calibration results, 12% less low flows). These small errors are still present in the scenario simulations and need to be taken into account in the analysis of the scenario results.

The impact of the 100-year logging rotation on water yield is very small. The first rotation low flows are not discernibly different from the observed low flows, while the second rotation low flows are generally 15% lower than the observed low flows. Considering that the lowest 40% of flows were 12% lower than the observed in the calibration, there is very little difference in low flows between the second rotation and the calibration. The impacts of the 50-year and 20-year logging rotations on water yield are slightly more than the 100-year impact. The 20-year forest and tree-farming scenario has the greatest impact of the scenarios, reducing low flows by 25% relative to the observed.

Table 2 Impact on mean daily flow (Mean – in ML), percentage difference from the observed (Mean % Diff) and the average percentage difference from the observed for the lowest 40% of flows (Low % Diff) for all scenarios.

Scenario	Rotation	Mean	Mean % Diff	Low % Diff
Observed		465		
Calibration		480	3	-12
100 Year Forest	1st	440	-5	-5
	2nd	393	-15	-15
50 Year Forest	1st	436	-6	-6
	2nd	368	-21	-20
20 Year Forest	1st	451	-3	-4
	2nd	370	-20	-21
20 Year Forest & Tree Farm	1st	448	-4	-4
	2nd	310	-33	-25

4.4. Discussion

The main determinant of a logging rotations impact on total runoff and low flows is the degree to which the logged species contributes to total runoff and low flows. The calibrated Macaque was run for the year 1962 in order to investigate the contribution to total runoff and low flows during the climatically average year for each species. Table 3 presents the percentage of the catchment area (% Area) covered by each species and the percentage of total rainfall (% PA) received and total runoff (% RA) produced from that species. Table 3 also contains the percentage of precipitation received (% PS) and runoff produced (% RS) from each species for the three months with the lowest flow (January, February and March). The *E. nitens* and pinus species (see Figure 2) are not present in Table 3 since they are not the dominant species in any ESUs.

Table 3 Percentage of catchment area covered by a particular species, precipitation received and runoff produced for annual and the driest three months of 1962 for the North Esk catchment.

Vegetation Type	% Area	% PA	% RA	% PS	% RS
E. regnans	61.3	58.9	36.9	58.0	29.3
Grassland	11.8	10.8	17.8	10.3	4.2
E. obliqua	17.9	19.0	25.7	19.8	32.9
Acacia dealbata	1.6	1.5	1.0	1.5	0.3
Nothofagus cunninghamii	2.6	2.6	1.7	2.6	0.3
Heath	3.1	5.0	11.7	5.5	22.9
Rocky	1.7	2.2	5.3	2.4	10.1

Under the 1962 climate the *E. regnans* logging scenarios can modify 36.9% of the total runoff and 29.3% of the runoff in the driest three months, while the *E. regnans* logging and tree-farming scenario can modify 54.7% of the total runoff and 33.5% of the runoff in the driest three months. Table 3 also reveals that 45.3% of the modelled total runoff and 66.5% of the modelled runoff in the driest three months is unaffected by changes in vegetation age or type introduced by the logging rotation and tree-farming scenarios.

The narrow range of impact on water yield seen in the logging and tree-farming simulation results is due to the proportion of total runoff and driest three months runoff that is unaffected by those scenarios. The impact of the logging and tree-farming scenarios on mean daily runoff ranged between reductions of 15% to 33% for the second rotation. Considering that the areas modified contribute 54.7% of total runoff, these reductions represent significantly impacted runoff (27-60% reductions) from those modified areas. The impact of the logging and tree-farming scenarios on the lowest 40% of flows ranged between reductions of 15% to 25% for the second rotation. Considering that the areas modified contribute 33.5% of the runoff for the three driest months, these reductions represent highly impacted runoff (45-75% reductions) from those modified areas.

The modelled impact on low flows is smaller than the modelled impact on mean daily runoff due to the unmodified areas of the catchment contributing a larger proportion of runoff for low flows than for total runoff.

5. CONCLUSIONS

The spatial process model Macaque was successfully applied to the North Esk catchment in order to assess future impacts on the level of summer low flows due to potential changes in catchment vegetation age and type. Several logging rotation scenarios and a logging and tree-farming scenario were modelled. The impact of the logging and tree-farming scenarios ranged from a 15% to 25% reduction in low flows relative to the observed. In the North Esk catchment, mountainous regions provide a high proportion (66.5%) of summer low flows that remain unaffected by, and thus limit the impact of, the simulated land use changes. Runoff from the modified areas of the catchment were significantly impacted by the logging and tree-farming scenarios.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Kuczera, G., Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest, *Journal of Hydrology*, 94, 215-236, 1987.

McClenaghan, M.P., & C.R. Calver (comp.), Geological Atlas 1:250000 digital series, Geology of Northeast Tasmania, Tasmanian Geological Survey, 1994.

Nash, J.E., and J.V. Sutcliffe, River flow forecasting through conceptual models, 1. A discussion of principles, *Journal of Hydrology*, 10, 282-290, 1970.

Peel, M.C., F.G.R. Watson and R.A. Vertessy, Modelling of low flows in the North Esk River using the Macaque model, Report prepared for Launceston City Council, Pages 52, 2002.

Roberts, S.L., R.A. Vertessy and R.G. Grayson, Transpiration from Eucalyptus sieberi (L. Johnson) forests of different age, *Forest Ecology and Management*, 143, 153-161, 2001.

Vogel, R.M. and N.M. Fennessey, Flow-Duration Curves. 1: New Interpretation and confidence intervals, *Journal of Water Resources Planning and Management*, 120(4), 485-504, 1994.

Watson, F.G.R., Large scale, long term modelling of the effects of land cover change on forest water yield, PhD thesis, Dept. of Civil and Environmental Eng., The University of Melbourne, Australia, 1999.

Watson, F.G.R., R.B. Grayson, R.A. Vertessy and T.A. McMahon, Large-scale distribution modelling and the utility of detailed ground data, *Hydrological Processes*, 12, 873-888, 1998.

Watson, F.G.R., R.A. Vertessy and R.B. Grayson, Large-scale modelling of forest hydrological processes and their long-term effect on water yield, *Hydrological Processes*, 13, 689-700, 1999.

Watson, F.G.R., R.B. Grayson, R.A. Vertessy, M.C. Peel and L.L. Pierce, Evolution of a Hillslope Hydrologic Model, In MODSIM – International Congress on Modelling and Simulation, Canberra, December, 461-467, 2001.