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The Use of Mathematical Models in Evaluating Forest Treatment Effects on Streamflow

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SUMMARY The use of mathematical models in quantifying effects of forest treatment on streamflow yield, based on the paired catchment approach (Climate Index Model) and the single catchment approach (Soil Dryness Index Model) is demonstrated. Application of the calibrated models to the Black Spur group of catchments near Healesville in Victoria shows increases in yield from the patchcut to be sustained while initial yield increases in the uniformly thinned catchments decayed rapidly.

1 INTRODUCTION

Melbourne and Metropolitan Board of Works harvests water from forested catchments in the Central Highlands to the north and east of Melbourne and maintains the policy originally formulated by the State Government of managing its traditional catchments solely for water supply purposes. The Board, recognising the need for a scientific understanding of the role of the forests in affecting streamflow yield, commenced its catchment hydrology research program in 1948. As a result of a ministerial directive, the program was significantly expanded in 1968 with the overall objectives of catchment hydrology research being to examine the effects on water yield and water quality of both natural and man-made changes in the forest environment and to determine the implications of such effects for large water supply catchments and headworks systems (O'Shaughnessy 1986). In order to achieve the above objectives, the Board established a number of experimental watersheds in the Maroondah catchment near Healesville. The paper presented herewith reports on techniques used to evaluated changes in streamflow yield due to two silvicultural practices; namely patch cutting and uniform thinning of forests.

The paper begins with an introduction to the Board's experimental catchment program and research associated with data collected from these catchments. There follows a description of two hydrologic models, a regression type climate index model and a process type Soil Dryness Index model. The paper concludes with the application of these models to the Black Spur Group of catchments to evaluate changes in streamflow yield due to patch cutting and uniform thinning of forests.

2 DESCRIPTION OF THE EXPERIMENTAL CATCHMENT AREA

Melbourne obtains 90% of its average annual water supply requirements from upland catchments located in the dividing ranges to the north and east of Melbourne. Excluding the alienated lands of the lower Yarra catchment, nearly all the land in the watershed is forested. Ash type species, with Mountain Ash (Eucalyptus regnans) being the main species, forms the dominant forest cover on 50% of the area. It is estimated that 80% of the average annual streamflow is derived from the 50% of the catchment carrying ash type forest. About 20% of the ash type forest is over 150 years old and the remainder is regrowth mainly originating from the 1939 wild fires.

Two major sets of catchment experiments have been established; one in oldgrowth Mountain Ash forest at Coranderrk near Healesville and the other in largely regrowth forest at North Maroondah. A total of 17 catchments has been established ranging in size from about 4 to 50 ha. As well, the Board and the Department of Conservation, Forests and Lands co-operate in a joint experiment in a 120 ha. catchment located at Narbethong close to the North Maroondah set of catchments.

The North Maroondah experimental area has been subdivided into four groups of experimental catchments; Black Spur, Myrtle, Ettercon and Monda groups. A full description of the catchments is given in Langford and O'Shaughnessy (1980a). Experiments conducted in these catchments involve the measurement of various elements of the catchment water balance components before and after the application of a number of timber harvesting treatments. Included in these elements are rainfall, canopy interception, soil moisture and streamflow. These measurements are supplemented by the continuous monitoring of forest stand parameters such as stocking rate, basal area, crown cover and leaf area.

This paper specifically deals with the Black Spur group of catchments which has undergone a patch cutting and a uniform thinning treatment in 1977. Specific treatments given to the catchments are detailed in Table 1.

Figure 1 is an aerial view of the Black Spur group of experimental catchments showing effects of treatments carried out during 1977.

Table I Details of treatments carried out in the Black Spur group of catchments

CATCHMENT	AREA (ha)	TREATMENT METHOD	POST TREATMENT ACTION
Black Spur 1	17.0	50% patch cut	patches replanted
Black Spur 2	9.6	40% uniform thin	nil
Black Spur 3	7.7	50% uniform thin	nil
Black Spur 4	9.8	none - control	

Figure 1 Aerial view of the Black Spur catchment group showing the effects of treatments carried out during 1976/1977

3 METHODOLOGY

The effects of different land use changes and silvicultural practices upon streamflow yield have been studied by many researchers. Research reported includes, the effects on streamflow yield due to conversion of grass or scrubland to forests (Carbon et al. 1982), changes in species type (Tsykin et al. 1982), forest stand age (Bosh 1979, Langford and O'Shaughnessy 1980b) and temporary or permanent reduction in forest cover (O'Shaughnessy and Moran 1983, Verry 1986, Troendle and King 1987). Effects of various forms of land use on long-term streamflow yield have also been studied (Aston and Dunin 1980, Ronan et al. 1982).

Two popular methods exist to determine the effects of land use change (treatment) on various components of the catchment water balance. The first method belongs to the 'control or the paired catchment' approach, in which the catchment subjected to some form of treatment is compared with an untreated control catchment in a similar environment. Information from the pre-treatment calibration period is used to develop mathematical relationships between the control catchment and the catchment destined for treatment. These relationships are then used with control catchment information during the post-treatment period to predict conditions that would have prevailed in the treated catchment in the absence of treatment. The difference between observed and model predicted data is presumed to be the effects of treatment. The second approach involves the use of a single catchment. A mathematical model is calibrated with pre-treatment data and convoluted with post-treatment climate inputs to predict conditions that would have existed had the land use changes not been made. Differences between observed and predicted post-treatment values are considered to be the effects of treatment.

Both methods attempt to quantify the effects of treatment independent of different climate sequence in the post-treatment period. While the paired catchment approach may be more expensive to conduct, data obtained from such tests provide a quick means of establishing and quantifying post-treatment trends in yield. The application of a hydrologic model depends on the ability of the model to adequately represent the hydrologic processes and the methods used in calibrating the model. The use of both methods is demonstrated in calibration and application of the models to the Black Spur group of catchments.

3.1 Climate Index Model

The Climate Index Model which is a regression method, involves the use of streamflow data from the control catchment as an index of natural temporal variation. At the time of treatment, the Black Spur 4 catchment was considered to be the control catchment and was left untreated. However, analysis of post-treatment data found runoff from the catchment to be abnormally low. Hence its role as the control catchment was replaced by the nearby Ettercon 3 catchment. The regression relationship developed for annual runoff is of the form:

$$QT(i) = a(i)\ QC + b(i) \qquad (1)$$

where,

$QT(i)$ = annual runoff (mm) from the ith Black Spur catchment, i = 1 to 3

QC = annual runoff (mm) from Ettercon 3 catchment

$a(i), b(i)$ = regression coefficients

i = the number of the Black Spur catchment

Parameters a(i) and b(i) are fitted to runoff using the program suite NLFIT (Kuczera 1982a). NLFIT, which is an interactive program specifically designed for fitting non-linear hydrologic models, uses the Gauss-Marquardt algorithm to optimise the parameter vector. Theoretical development and practical applications of NLFIT are described fully in Kuczera (1982a and b). Parameters derived in the calibration of the Climate Index Model with data from the Black Spur group of catchments are depicted in Table II.

Figure 2 shows observed and predicted annual flow from the three Black Spur catchments. The use of the calibrated models with post treatment data is described in Section 4.

Table II Calibration of the Climate Index Model

PARAMETER	CATCHMENT BS1 i=1	BS2 i=2	BS3 i=3
a(i)	109.37	218.49	223.12
	(18.4)	(39.8)	(11.6)
b(i)	0.949	0.873	0.746
	(0.042)	(0.091)	(0.027)
r^2	0.99	0.97	0.99

Note: values within brackets are standard deviations of the parameters.

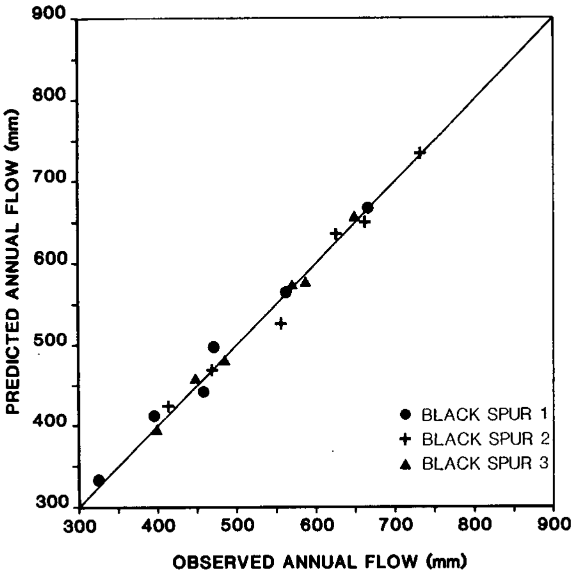

Figure 2 Observed and Climate Index Model predicted annual streamflow yield.

3.2 Soil Dryness Index (SDI) Model

The SDI model explicitely describes the dominant hydrologic processes involved in converting rainfall into runoff. The model, which is a mathematical water balance model, was first developed by Mount (1972) and subsequently modified by Langford et al. (1978). Kuczera (1984) in a major revision of the SDI model, changed the basic model structure and modified the algorithms of a number of key hydrologic processes. The evapotranspiration algorithm was completely modified and a deep seepage parameter introduced. Improvements were also made in parameter estimation with the coupling of an objective calibration strategy ie. program suite NLFIT. Kuczera's 1984 revisions significantly improved the models predictive ability, made the model more physically realistic and increased the confidence of estimated parameters. Figure 3 illustrates the structure of the SDI model made up of fluxes, functions and stores.

Flux equations of the SDI model are as follows:

Throughfall + Stemflow [T(t)]

$$T(t) = \begin{cases} B\,P(t) - A & \text{if } T(t) > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$

where,

A,B = Throughfall parameters
P(t) = Daily rainfall (mm)

Flash runoff (FLASH)

$$FLASH = FLH\;T(t) \qquad (3)$$

where,
FLH = Flash runoff parameters

Evapotranspiration [ET(t)]

$$ET(t) = D_f\;AEP\;PE(t)\;g_1\;g_2 \qquad (4)$$

where,

D_f = fraction of daylight hours
t = current day
AEP = evapotranspiration parameter
PE(t) = pan evaporation (mm)

$$g_1 = \max\{0, \min[1, 1 - \delta\left(\frac{S(t-1)}{SMIN}\right)^2]\} \qquad (5)$$

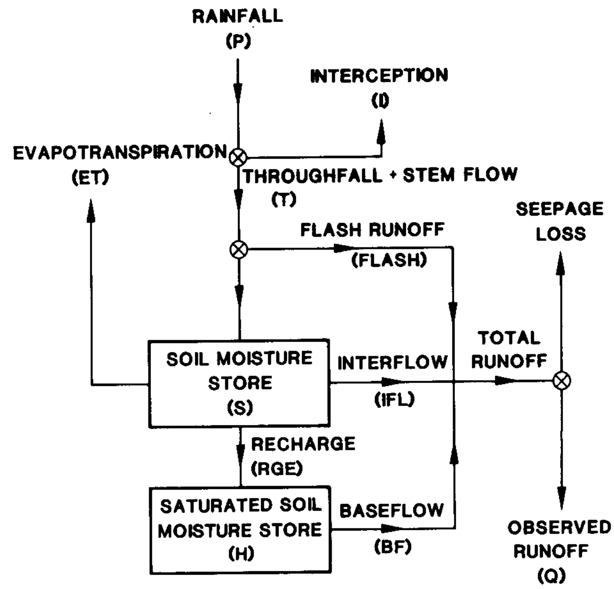

Figure 3 Schematic representation of the Soil Dryness Index Model

S = soil dryness index level
SMIN = minimum soil dryness index
δ, β = evapotranspiration parameters

$$g_2 = \max\{0, \min[1, 1 - \beta\;PE(t)]\} \qquad (6)$$

Interflow IFL(t)

$$IFL(t) = \begin{cases} KI\,[SMIN - S(t-1)] & \text{if } > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (7)$$

where,

KI = Interflow parameters

Recharge RGE(t)

$$RGE(t) = \begin{cases} -KR\,[S(t-1)] & \text{if } S(t-1) < 0 \\ 0 & \end{cases} \qquad (8)$$

where,

KR = Recharge parameter

Baseflow BF(t)

$$BF(t) = \begin{cases} KG\,[H(t-1)] & \text{if} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (9)$$

where,

KG = Baseflow parameter
H = Saturated store level

Equations (2) to (9) model input/output flux from hydrological processes and assist in the daily updating of the 'store' components of the SDI model. Daily rainfall and pan evaporation act as input to the model. The residual between observed and predicted monthly flow volumes was minimised in evaluating the 12 parameters of the model. Optimisation of the model was conducted in two stages; field estimates of model parameters were first made where possible and the remaining model parameters optimised through a trial and error procedure. Observed annual flow volumes are plotted against predicted monthly flow values (summed up over the year) in Figure 4. The use of the calibrated model in evaluating effects of treatment is described in Section 4.

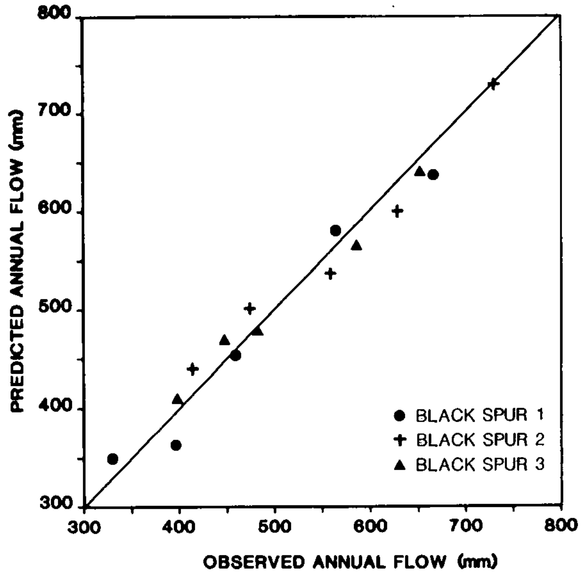

Figure 4 Observed and SDI model predicted annual streamflow yield

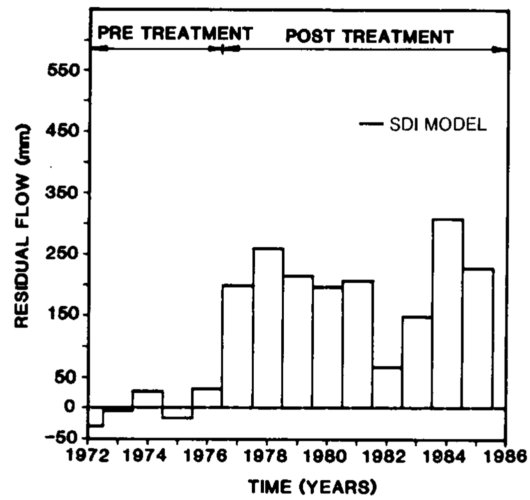

Figure 6 Residual annual flow due to patch cutting in Black Spur 1

4 SHORT-TERM EFFECTS OF TREATMENT ON STREAMFLOW

The Climate Index and the SDI model, calibrated for the Black Spur group of catchments, were used to quantify the effects of treatment on streamflow. Some preliminary results of the effects of forest treatment on water yield are presented to illustrate the use of the Climate Index and the SDI model. Application of the SDI model to BS 1 which had 50% of its basal area removed in a patchcut is shown in Figure 5. Differences between observed and predicted flows in the post-treatment period show the effects of treatment.

Residual streamflow from BS 1 is shown in Figure 6. Trends in post-treatment residuals show a substantial increase in yield just after treatment. Furthermore, initial increases in yield have been sustained over the past 8 years. A study of the water balance components of the SDI model show transpiration to be the largest of the loss components. A 50% reduction in basal area would substantially reduce the demand for water and leave more water for the replenishment of the soil mantle. Although the cut patches were regenerated with planted stock, the effects of the regenerated area on catchment evapotranspiration could be reduced by the shelter from radiation and wind given by the surrounding larger trees. This may partly explain the continuing increase in yield.

A residual flow plot from the BS 3 catchment which had 50% of its basal area removed by uniform thinning is shown in Figure 7. Streamflow yeild in the first two years increased substantially. Although the 50% patchcut in BS 1 matches the 50% uniform thinning in basal area in BS 3, yield increases from uniform thinning are significantly lower than the patchcut yield. The temporary increases in yield were found to decay rapidly with time as the canopy of the remaining trees expanded its surface leaf area (to occupy the additional space created by the felled trees), and the understory recovered from the trampling and general disturbances caused by the felling operations.

Figure 7 also compares residual flow predictions from the climate index model with predictions from the SDI model. The climate index regression model predicts residual flows on an annual basis and provides a simplified tool for quick predictions of yield trends. The physically based SDI model, once calibrated, provides valuable information on each water balance component of the catchment. As Figure 7 indicates, the post-treatment residual flows simulated by the two models show similar trends, although absolute values of annual flow residuals differ appreciably in some years. However, the application reported herein demonstrates the usefulness of both models and the concepts underlaying their development in forest hydrology, namely the paired and the single catchment approach to the detection of streamflow trends due to treatment.

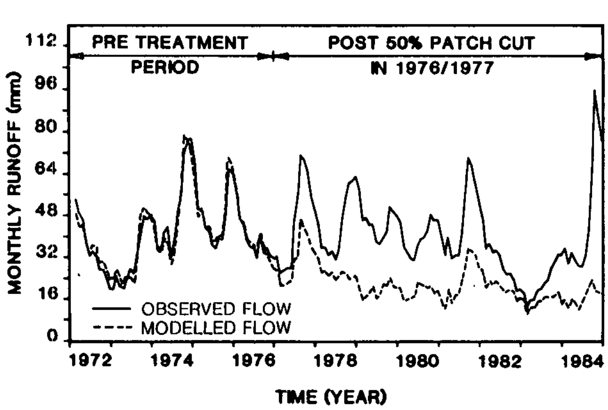

Figure 5 Modelling effects on monthly streamflow due to patch cutting in Black Spur 1

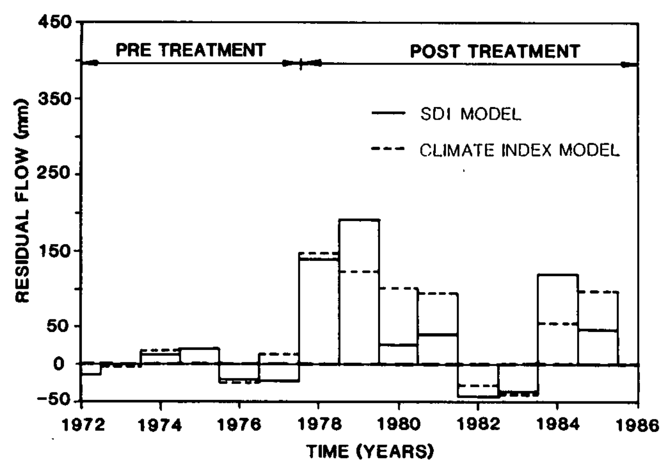

Figure 7 Comparison of Climate Index Model and SDI model predictions in Black Spur 3

5 SUMMARY AND CONCLUSIONS

The paper demonstrates the use of mathematical models in predicting short-term effects of treatment on streamflow. The models described were based on the paired catchment approach (Climate Index Model) and the single catchment approach (Soil Dryness Index Model). Preliminary application of the models to the Black Spur group of catchments showed initial increases in yield for the patchcut to be sustained while the yield increases in the uniformly thinned catchments decayed rapidly.

Research reported herein considers only short term changes in streamflow due to treatment. Experimental data from the treated catchments in the Coranderrk area (clear felling and selected cutting) are showing the importance of monitoring long-term effects on streamflow. Post-treatment catchment yield, after an initial increase, has shown signficant decreases in streamflow (Langford and O'Shaughnessy 1980b). Similarly, long term monitoring of the Black Spur group of catchments would give a better understanding of the interaction between treatment effects and streamflow yield as more information on streamflow and forest growth patterns becomes available. A report on the Black Spur group of catchments with a detailed analysis of the effects of treatment on each water balance component of the catchment is under preparation (Jayasuriya and O'Shaughnessy 1988).

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