Assessment of Three Models to Predict Post-treatment Effects on Streamflow from a Small Forested Catchment

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Abstract The water yield changes after forested catchment conversion at Clem Creek (located southwest of Myrtleford, Victoria, Australia) provided an opportunity to assess the efficiency of the three models which are an antecedent precipitation model, a pseudophysical model, and a paired catchment regression model. Assessment of the three models, showed that the paired catchment regression model gave the most satisfactory representation of the hydrology at Clem Creek during pretreatment and post-treatment periods. This model indicated that clearing and removal of the vegetation from the eucalyptus forest and replacing it by a pine forest in the small forested catchment led to streamflow increase in the first few years after treatment.

INTRODUCTION

Water balance models are crucial for predicting water yield. In particular, these models can be applied in a small forested catchment after removal of vegetation [Sittner *et al.*, 1969; Stoke and Loh, 1982; Topalidis and Curtis, 1982; Cheng, 1989; Keppeler and Ziemer, 1990; Bren and Papworth, 1991]. This paper describes the assessment of three models to predict water yield after changes in land use. The models were a paired catchment regression model [Bren and Papworth, 1991], an antecedent precipitation index model [Fedora and Beschta, 1989] and a pseudophysical model [Boughton, 1984].

The aim of this study was to use Cropper Creek data to assess the predictive ability of data from a neighbouring catchment, a statistically based "black box" model and a pseudophysical model, and to compare the efficiency of prediction of the effects of catchment land use changes at times when the neighbouring catchment data are not available. The pseudophysical model was tested to see if it could be used to estimate changes in the internal hydrology of the treated catchment due to the land use changed.

MATERIALS AND METHODS

Study Area and Treatment

The study area included Clem Creek, Ella Creek and Betsy Creek having catchment areas of 46ha, 113ha and 44ha respectively, located in the valley of Croppers Creek, 23 km southwest of Myrtleford (Victoria) (Figure 1). Elevations range from 250 to 470 m. The study site is located about 2 km south of a large forestry plantation. The slopes range from 10^{o} - 30^{o}, with the concentration falling into 20^{o} - 25^{o}. Lower slope forest is predominantly narrow-leaf peppermint (*Eucalyptus radiata* Sieb.). Exposed slopes tend to favour broad-leaf peppermint (*E. dives* Schauer) and brittle gum (*E. mannifera* Mudie). The lower slope understorey is Austral bracken (*Pteridium escalentum* Nakai). The lapidarian zone carries the densest vegetation and the largest trees, comprised of candlebark gum (*E. rubida* Labill) with an understorey of dense thickets of common ground fern (*Culcita dubia* Maxon) [Bren and Papworth, 1991].

Bren [1979] described the geology and soil in this area: the dominant rock types were quartzite, sandstone and slate. The only soil type found on the catchment is a red-brown loam. Soil on the lower slope is a stable red clay-loam passing suddenly into weathered parent rock at 2 m. The upper slope soil is skeletal and undeveloped.

Rainfall records for the study area indicate an annual average of about 1400 mm with temperature ranges from -3 ^{o}C to 40 ^{o}C. Most of the precipitation is in the form of rain, with infrequent snowfalls. Before treatment, maximum annual rainfall values were over 1800 mm; during the cutting, maximum annual rainfall recorded was 2000 mm. After conversion from eucalypt forest to radiata pine plantation, maximum annual rainfall values were still over 1800 mm. Winter storm rainfalls tended to be long periods of low intensity (5 - 20 mm h^{-1}) rain. Summer storms tended to be short-duration, mostly of convective origin with a higher intensity (20 - 60 mm h^{-1}) (Bren and Papworth, 1991).

Streamflow measurements commenced in May 1975. In December 1979 the dry sclerophyll vegetation on the slopes of Clem Creek was flattened using three heavy bulldozers. This standard clearing technique (at the time) involved two of the tractors pulling a heavy chain downslope, with a third crawler acting as a "pusher" for particularly resistant trees. To protect the stream a 30-m-wide buffer strip (either side of the stream) was left. This was delineated by a rough track used to allow the crawler tractors to turn around and to move along the length of the catchment. Because of the steepness of the slopes, the debris could not be effectively heaped, so this was broadcast burnt in April 1980. The surface was left completely devoid of live vegetation and pitted with depressions left by the root fans of the overturned trees. The area was then hand-planted with radiata pine [Bren and Leitch, 1986]. Aspects of the catchment ranged from northeast to southeast, the northern slopes being more exposed to insulation and generally drier.

Data

The study data has been divided into three periods, including the calibration period (1975 - 1977), the verification period (1978 -1979), and the post-treatment period (1980 -1987). Each of the models was utilised for full range and low flow (December - May).

For the three models, there are inconsistencies in data input. For the antecedent precipitation index model, the rainfall was the input. The streamflow of Ella Creek was the input for the paired catchment model. There were more input factors for the pseudophysical model (Table 1). Hence, the physical stage was significantly unlike for the three models.

Antecedent Precipitation Index Model

The antecedent precipitation index (API) model was based on recession analysis [Garstka *et al.*, 1958] to define the beginning and ending of a runoff event. The effect of antecedent precipitation on streamflow was assumed to "decay" at the same rate as the recession limb of a hydrograph during periods without rainfall [Fedora and Beschta, 1989].

In the analyses of the API model, a regression equation and a 95% confidence limit for the calibration period were developed for each selected streamflow without rainfall against streamflow preceding those observations at a specified time interval. In the following equation (1) K indexes the effectiveness of the antecedent precipitation upon rainfall-runoff processes for the calibration period.

$$API_t = API_{t-\Delta t}K + P_{\Delta t} \qquad (1)$$

where $API_{\Delta t}$ is the antecedent precipitation index (mm) at time Δt; $API_{t-\Delta t}$ is the antecedent precipitation index (mm) at time t-Δt; K is the recession coefficient ; Δt time interval (day) between precipitation observations; and $P_{\Delta t}$ precipitation (mm) during the time interval from $t\text{-}\Delta t$ to Δt. Thus the relative importance of antecedent precipitation upon API_t depends not only upon the amount of precipitation, but also upon the number of time intervals between its occurrence and time t.

Simple linear regression was used to develop relationships between the square root of storm runoff and corresponding values of API_t (at daily intervals) for the selected streamflows:

$$Q_t^{0.5} = I + S \times API_t \qquad (2)$$

where Q_t is the streamflow (mm) at time t, and I and S represent the intercept and slope respectively. A recession factor of 0.882 and threshold value of 0.1 mm of the antecedent precipitation index were found to satisfactorily estimate hydrograph response at the Clem Creek catchment during the calibration period.

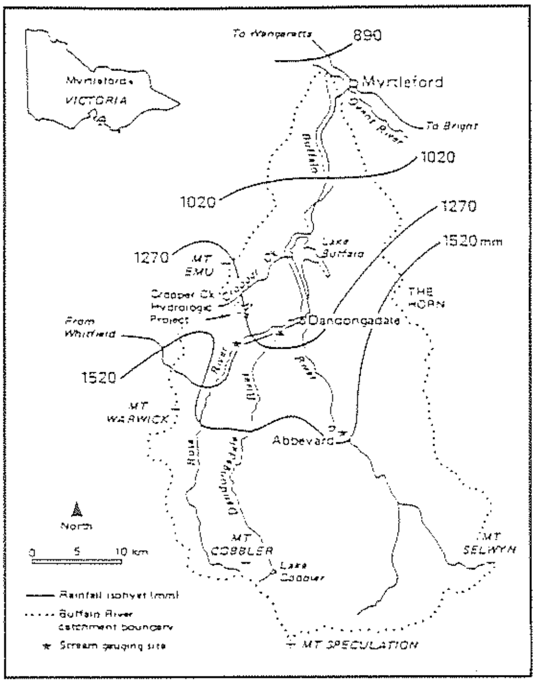

Figure 1. The location of the study area.

Table 1. Input and output for the three models

Model	Input		Output
	Parameters	Variables	
API	None	Rainfall (mm)	Streamflow (L/s)
Paired	None	Streamflow of Ella Creek (L/s)	Streamflow (L/s)
SFB	S F B	Rainfall (mm) Evaporation (mm)	Streamflow (L/s)

The Pseudophysical Model

The pseudophysical model which is called simple conceptual daily rainfall-runoff model is designed to approximate with its structure the general physical mechanisms of the hydrologic cycle.

The simple conceptual daily rainfall-runoff model [Boughton, 1984] which was developed primarily for estimating water yield of ungauged catchments in Australia represents a certain component in the processing of the hydrologic event. This model used daily rainfall and pan evaporation data as input, and streamflow as output. In this model, three parameters were used to determine the processes of generated runoff. These parameters are surface storage capacity (S), daily infiltration capacity (F) which controls percolation from the surface store to the ground water store, and baseflow factor (B) which is used to determine the portion of the daily depletion of ground water that appears as baseflow runoff. As with the pseudophysical model, the ability of these models to integrate the complex catchment processes makes them powerful tools for studying the response of a large catchment to changes in vegetation management strategies [Leaf, 1975].

The successful application of the pseudophysical model depends on how well the model is calibrated. In recent years, automated approaches to calibration have received much attention, and several difficulties in the application of such methods have been reported [Ibbitt, 1970; Johnston and Pilgrim, 1976; Pickup, 1977; Sorooshian and Gupta, 1993; Gan and Burges, 1990a, 1990b; Duan *et al.*, 1992; Sorooshian *et al.*, 1993]. These reports indicate that it is typically difficult, if not impossible, to obtain a unique set of optimal parameters for the pseudophysical model using automatic calibration methods [Duan *et al.*, 1992]. However, a fundamental problem of the pseudophysical model is how to attempt "True" parameter values.

The remaining three parameters were selected for optimisation, and the feasible parameter space was specified by estimation of parameter values for use in the SFB model recommended by Boughton [1984]. The units hydrograph used for final routing was based on the observed hydrograph and was not included in optimisation. The parameters of this model (S = 200 mm, F = 80 mm/day, and B = 0.1) during the calibration period were obtained by the exhaustive gridding method. Figure 2 shows the values of the objective function as a function of the run number. It can be seen that the correlation coefficient obtained using the calibration data is, at best, relatively low ($R^2 = 0.212$) but there is a unique solution.

Paired Catchment Regression Model

In a study of the Cropper Creek project, Bren [1979] suggested that the paired catchment regression model could be used to estimate effects on water yield during the treatment period, because of displacement of the phrenetic divide between catchments due to the changed moisture conditions. A regression equation (3) and its 95% confidence limits for the pretreatment calibration period was developed for the selected streamflow variable using data from Ella Creek as the dependent variable. The calibration regression was developed using daily streamflow (July 1975 - July 1977). The pretreatment regression model provides an estimate of the streamflow of the study creek, Clem Creek, over the study period.

$$C^* = f(E) \qquad (3)$$

where C^* is the daily flow (L s^{-1}) of Clem Creek; and E is the daily flow (L s^{-1}) of Ella Creek. Streamflow changes in Clem Creek for the verification (July 1977-December 1979) and post-treatment (January 1980-July 1987) periods were evaluated according to the calibration model and independent period model. For a given streamflow variable, the calibration regression equation and observed post-treatment values of the control Ella Creek were used to compute what the corresponding estimated values for the Clem Creek would have been had its catchment not been treated. Observed and estimated streamflow values were then compared.

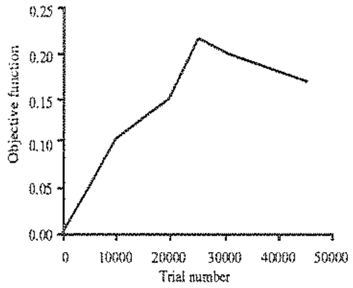

Figure 3. The best function values obtained using the exhaustive gridding algorithms.

Model Efficiency

In this study, the analysis was based on the studies of three models [Zhang, 1994]. Statistical parameters of observed and estimated streamflow derived from the three models, including mean, median, maximum, minimum and standard deviation, single mass plot of the cumulative observed streamflow and the cumulative estimated streamflow and the coefficient of efficiency E, were used to compare the efficiencies of the three models.

$$E = \frac{\sum_{i}^{n}(Obs_i - \overline{Obs})^2 - \sum_{i}^{n}(Est_i - Obs_i)^2}{\sum_{i}^{n}(Obs_i - \overline{Obs})^2} \qquad (4)$$

Equation (4) was introduced by Nash and Stutcliffe [1970] and is called the coefficient of efficiency. It expresses the proportion of variance of the observed flows which can be accounted for directly by the model. A value of E close to unity indicates that the model can satisfactorily reproduce the observed flows, with E=1.0 indicating that the estimated flows for all time steps are the same as the observed flows, and E can take a negative value, which implies a poor model estimation. James and Burges [1982] suggested that E should exceed 0.97 for model acceptance.

Table 2. Summary of the coefficient of efficiency for the three models during the calibration period.

Model	E
API	0.423
SFB	-0.210
Paired	0.988

Table 3. The coefficients of API model and paired catchment regression model, and the parameters of SFB model during the calibration and post-treatment periods.

Period	API			Paired		SFB		
	K	Intercept	Slope	Intercept	Slope	S	F	B
Calibration	0.882	0.480	0.470	0.046	0.594	200	80	5
Post-treatment	0.829	1.056	0.570	0.056	2.054	290	0.10	1.00

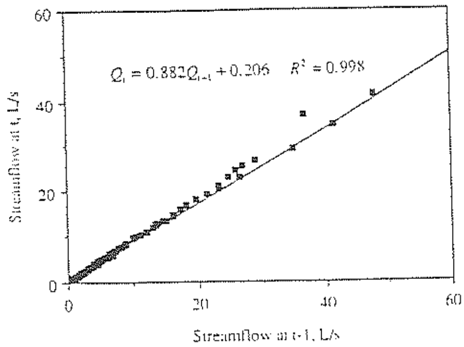

Figure 3. The recession limb data for Clem Creek during the calibration period.

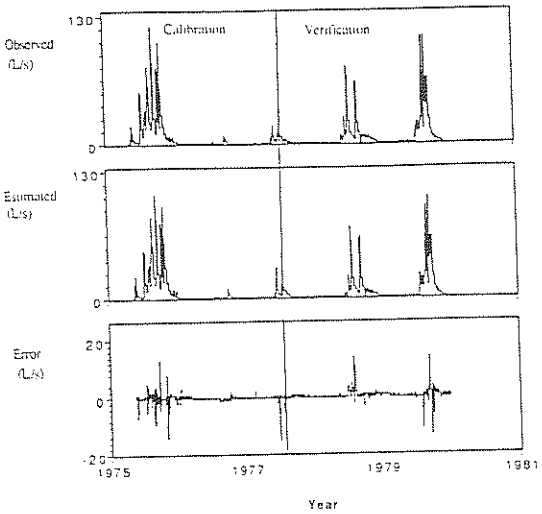

Figure 4. The observed, estimated streamflow and error for the calibration and verification periods for the paired catchment regression model.

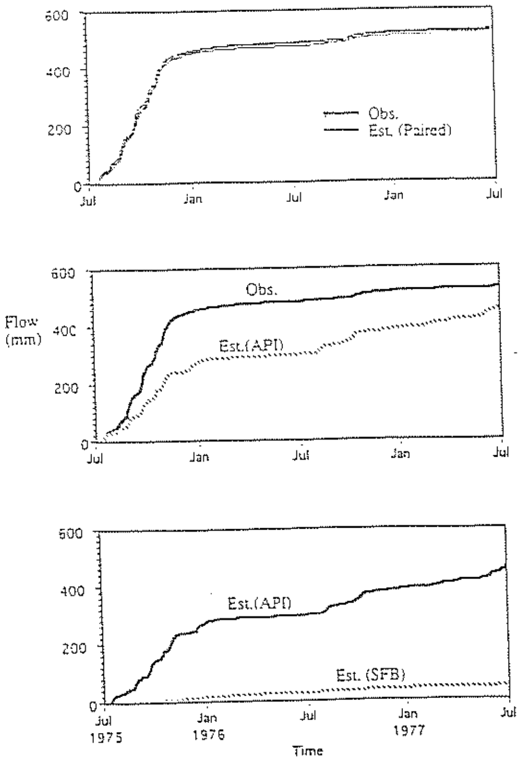

Figure 5. Single mass plots of cumulative observed streamflow of Clem Creek and cumulative estimated streamflow for the three models.

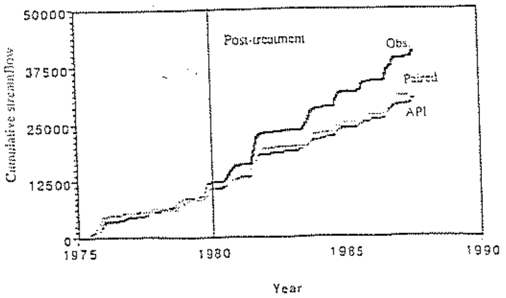

Figure 6. Single mass plots of cumulative observed and estimated streamflows derived from the calibration period API and paired catchment regression models.

RESULTS

Figure 3 shows the recession limb data decay (i.e. flow at time t as a function of flow at time t-1) for the API model. As expected in such a relation some heteroscedacity was present which makes it difficult to assign error limits. The recession coefficient was ultimately taken as 0.882.

Table 2 summarises the coefficient of efficiency for the three models, and Table 3 summarises the statistical parameters for the three models during the calibration period.

Figure 4 shows the observed, estimated streamflow and error estimates for the calibration and verification periods for the paired catchment regression model. It can be seen that the regression model provides an excellent estimate of the pre-treatment Clem Creek flows. Figure 5 shows single mass plots of cumulative observed and estimated streamflows derived from the calibration period API and paired catchment regression models. Single mass plots of cumulative observed streamflow of Clem Creek and cumulative estimated streamflow for the three models are shown in Figure 6. The cumulative estimated streamflow derived from the regression model and the cumulative observed streamflow of Clem Creek show close agreement for the pretreatment period. In contrast, the trend of the cumulative estimated streamflow derived from the calibration period API model is less than the cumulative observed streamflow of Clem Creek. The agreement between estimates based on the SFB model and the observed data are poor by any standards.

DISCUSSIONS

The results showed that neither API model nor the SFB model give a really satisfactory representation of the hydrograph, although each could reproduce general hydrologic features obtained during the course of the year. Doubtless, further work could improve the efficiency of prediction in either case, but it would seem unlikely that either could replace the use of a neighbouring catchment as a predictor of flow. Results show that neither model can be used to improve accuracy of prediction during the period when the control catchments were not flowing. Further, the accuracy of the SFB is not great enough to warrant being used to help provide insight into the nature of hydrologic changes engendered by clearing the eucalypt vegetation off the catchment slopes.

The results (Table 2, Figure 5) showed the API and SFB models failed to estimate water yield during the calibration period and to predict water yield changes after forested catchment conversion. This failure was probably due to limitations of the conceptualisation of the process. Comparison of the three models (Tables 2 and 3, Figure 5 and Figure 6) , showed that the paired catchment regression model gave the most satisfactory representation of the hydrograph at Clem Creek during pretreatment and post-treatment periods. This model (Figure 4) showed that clearing and removal of the vegetation from the eucalypt forest to a pine forest in the small forested catchment led to streamflow increase in the first few years after treatment. The results were similar to those of many other catchment experiments [Tsykin *et al.*, 1982; Pilgrim *et al.*, 1982; Keppeler and Ziemer, 1990].

Several authors have recently examined modelling problems in catchment hydrology and related fields, particularly in the use of physically based models. They originally appeared to hold out the promise of determining system response in terms of known processes and measurable parameters [Beven, 1989; Grayson et al., 1992; Wheater et al., 1992 and Barnes, 1993]. Barnes [1993] gave a detailed analysis of what constitutes a good model. They showed that regression models can obtain excellent representation of the data, with a minimum number of well chosen independent variables, but that they are very difficult to generalise or interpret physically. Physically based models represent processes and interactions but are not necessarily superior to conceptual parameter models for simplicity or for process understanding. This is particularly the case when these more complex physically based models cannot be supported in terms of available data. However, the best model is not necessarily the most complex, or the one which overtly reflects the most sophisticated understanding of the system.

CONCLUSIONS

The water yield changes after forested catchment conversion at Clem Creek provide an opportunity to assess the efficiency of three models (API, SFB, and the paired catchment regression models). Each of the models was viewed as a representative of a different philosophical approach. The three models were calibrated to the pre-treatment records.

From the results, it is concluded that neither the pseudo-physical nor the antecedent flow approach can be viewed as approaching the efficiency of the regression approach based on the behaviour of the neighbouring catchment. It is hence concluded that, on the basis of these models, there is little alternatively to the tradition "multiple catchment experiment" to gain information concerning land use effects.

The failure of the SFB model to achieve any validity was disappointing in that it had been intended to use this model to draw inferences on the hydrologic nature of the changes to the catchment wrought by the treatment. Given the low coefficient of determination of the model, it is unlikely that there could be much reliability placed on any such result.

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