

# Low Flows and Flow Reductions in Aforested Catchments

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## Introduction

The effect of afforestation on the low flow yield of catchments is of particular importance as it is during low flow periods that water shortages are felt most acutely, particularly by run-of-river water users. There is a general perception too that low flows are more significantly affected by afforestation than are total flows. The afforestation permit system controls the expansion of forestry on the basis of the estimated reductions in total streamflow from forestry areas. Because of the importance of low flows it was felt that this might be either a more appropriate or an additional criterion to use in considering permit applications. This is the second study commissioned to look at the specific effects of afforestation on low flows.

In an earlier study Smith and Scott (1992) presented models, based on the analysis of five catchment experiments, to predict the reduction in total streamflow and low flow. The authors analysed flows using monthly streamflow totals, and low flows were defined as all the **monthly flow volumes** below a level **exceeded 75% of the time** (on average, three months in the year). Separate curves were proposed for flow reductions due to afforestation with eucalypts and pines, and for optimal growing conditions as opposed to sub-optimal growing conditions. The technical subcommittee of the Afforestation Permit System Committee of the Department of Water Affairs and Forestry expressed doubts concerning the small difference between the reductions in total and low flows indicated by the models. A re-analysis of the catchment experiments was requested:

- (i) re-defining low flows at the seventieth percentile exceedance level (70th PEL),
- (ii) using daily flow volume as the computational unit for the analysis (as opposed to monthly flow volume) and
- (iii) including a study of low flow reductions in relation to dry years or drought periods, as it was felt that flow reductions in these years would be greater than in wetter years.

In this paper we report on the results of this re-analysis and, in addition, on:-

- (i) some characteristics of low flows in high rainfall forestry catchments in different climatic zones,
- (ii) reductions in low flow as a result of afforestation with both pines and eucalypts, and
- (iii) how one's definition of what constitutes low flow affects the results obtained in the analysis of flow reductions.

## Methods

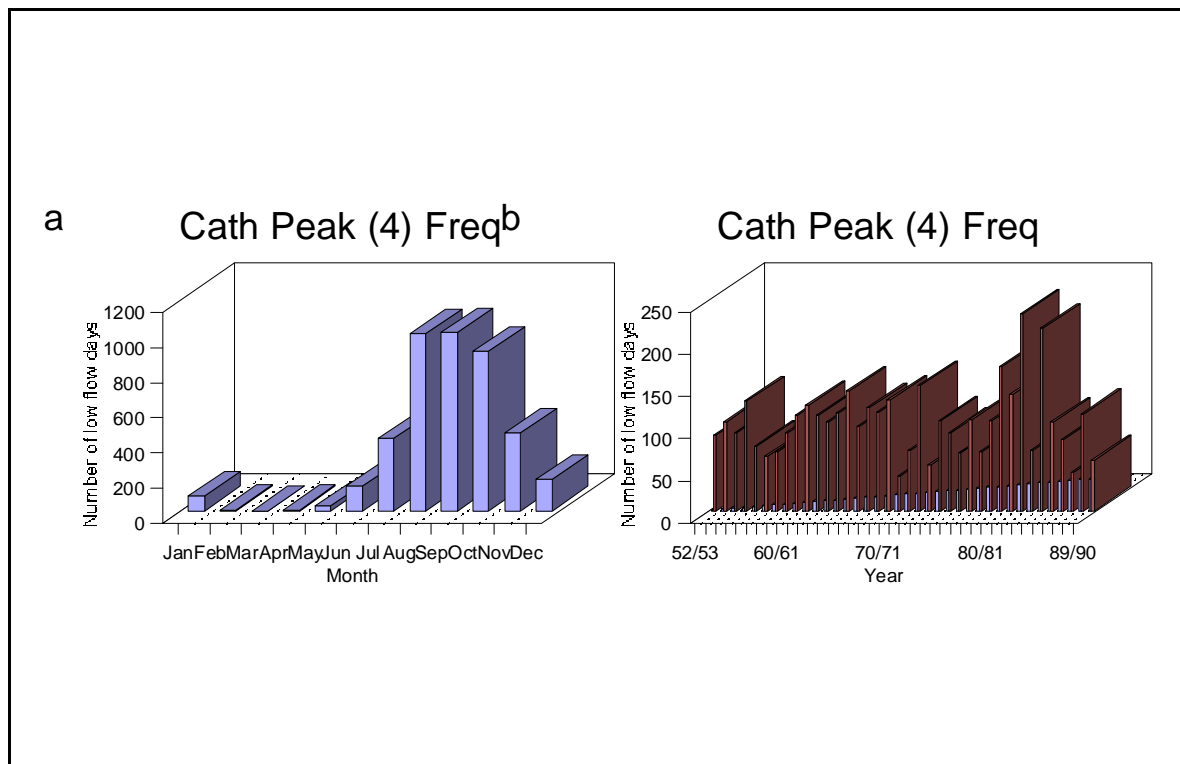
To check the work which had been done previously, the impact of afforestation in two experimental catchments was determined using daily flow volumes as the computational units and defining low flows at the 70th PEL (i.e. those below a level exceeded 70% of the time). Cathedral Peak catchment III (CIII), 86% afforested with pines (*Pinus patula*) in 1958, was used as a long streamflow record was available. Cathedral Peak catchment IV (CIV) served as the control. In effect this would test the flow reduction curves for pines in sub-optimal growth zones. The experiment at Westfalia, where catchment D was 100% afforested with *Eucalyptus grandis* in 1983, (Westfalia B as control) was used to check the model for eucalypts in optimal growth zones. As a final verification, flow from an independent catchment (Cathedral Peak CII, 72% afforested with pines in from 1951) - not used in the determining of the original flow reduction curves - was analysed and the results compared with the model predictions.

### **Defining the cut-off point for low flows**

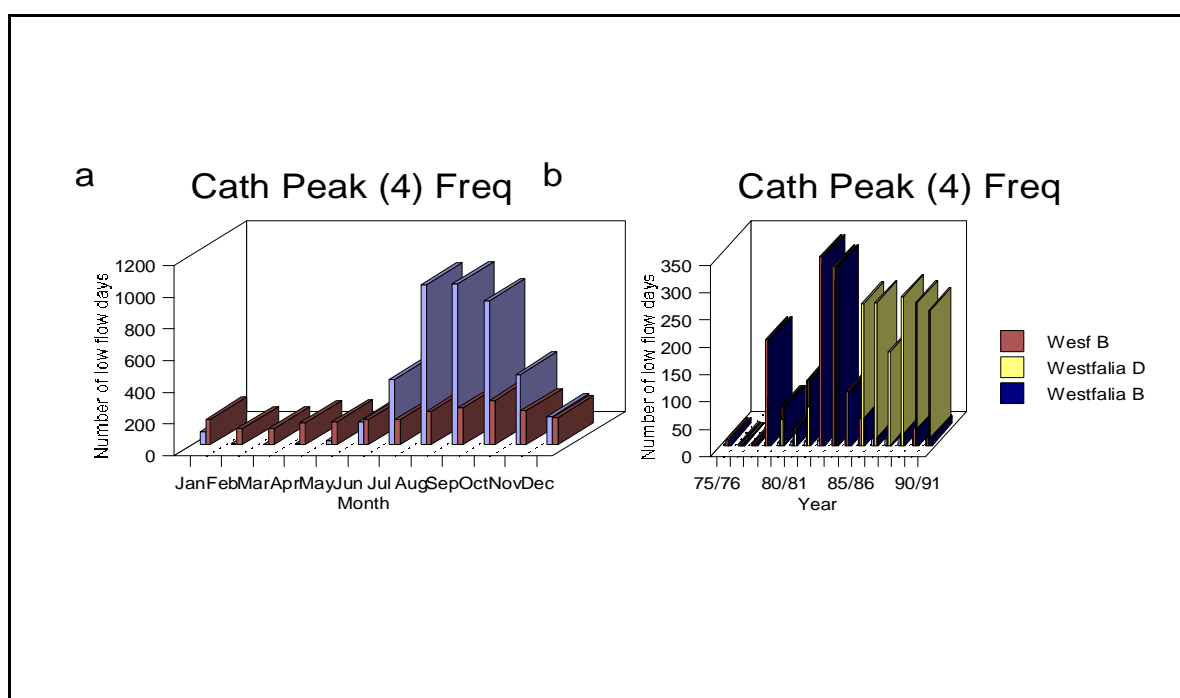
The daily flow data set for the control catchment for the full period of record was sorted in descending order, then ranked from 0 to 100 % using the 'Rank' procedure in SAS (1991). In this way all the daily flow volumes were ranked from 0% (for the highest daily volume) to 100% for the lowest daily flow volume. The cut-off point was chosen as that corresponding closest to the 70% ranking. The 70th PEL values established thus for Cathedral Peak CIV and Westfalia B were daily flow volumes of 0.6472 mm and 0.4092 mm, respectively. Data lines on days when daily flow in the control catchments exceeded these levels were deleted to create the low flow data sets.

The distribution of the resultant low flow days according to the above classification are shown in Figures 1 & 2, for Cathedral Peak CIV and Westfalia B respectively. These figures show a marked difference between Cathedral Peak and Westfalia. At the former low flows are a largely seasonal phenomenon with the frequency of low flow days per hydrological year being fairly evenly distributed (Figure 1b), though following apparent wet and dry cycles. Whilst at Westfalia low flows, though they have a seasonal character, are more of a drought period phenomenon, such that some years are entirely dominated by low flows and in other years few low flow events occurred (Figure 2b). The drought years in the early 1980's are apparent in both catchment areas.

A problem arose in determining a specific cut-off point for low flow at Westfalia because of the occurrence of two droughts in the study period. The droughts dominated low flows and largely established the cut-off volume, which was so low that there were few or no low flow days in the control catchment in some wetter years (Figure 2b). With a low 70th PEL, the actual number of low flow days in each year (particularly the normal and wetter years) was so low that many possible low flow days (in the treated catchment) in the last six years of record were not included in the low flow data set (Figure 2b). Application of the conventional definition therefore seemed likely to reduce the amount of information that could be derived on the effects of forestry on low flows.



**Figure 1** The frequency of low flow days at Cathedral Peak Catchment CIV (a) averaged by month and (b) per year from 1952 to 1990.



**Figure 2** The frequency of low flow days at Westfalia B, (a) averaged by month for the nineteen year period from 1975 to 1993, and (b) per year and as compared to the frequency in the afforested catchment (Westfalia D) of daily flow events below the same absolute exceedance level.

Two alternative approaches to the determination of the low flow data set were therefore tried at Westfalia.

- (i) The 70th percentile point in each hydrological year was determined and these values were then averaged over the years of study to obtain a higher exceedance level of 0.5329 mm, and consequently a larger low flow data set.
- (ii) Low flow was defined according to the 70th PEL in each hydrological year, which forced a sample of 30% in every year, both wet and dry.

The effects of afforestation on the streamflow were determined using the paired catchment method and using daily streamflow volume (mm) as the units of flow (computational units).

Calibration relationships (pre-treatment period) were obtained both for the full data sets (total flow) and for each of the low flow data sets (developed using different definitions). Each hydrological year (October to September) following the afforestation was then tested for a significant change from the calibration relationship using the dummy variable technique (Gujarati, 1978). Deviations from the expected flow (model predictions) were calculated as observed minus predicted streamflow, and this deviation also expressed as a percentage of the predicted flow, giving an annual percentage reduction in streamflow due to afforestation. The results from this study, using daily flow as the computational unit, were then compared to those of the initial study that used monthly streamflow values (Tables 1 & 2).

## Results

### Comparison of the reductions calculated using monthly and daily flow data

The re-analysis of afforestation effects on low flow using the daily flow values and the 70th PEL yields a very similar model of flow reduction to that produced using monthly flow volumes and a 75th PEL, with the actual reductions predicted by the different approaches being close (Tables 1 & 2, for Cathedral Peak CIII and Westfalia D respectively). Reductions also commenced at about the same time in both studies. The low flow and total flow reductions in the study using daily flow were significant ( $P < 0.05$ ) for each year where a change in streamflow is indicated in Tables 1 & 2. The absolute total flow reductions in both the monthly and daily flow studies are not particularly close, mostly as a result of averaging over monthly time periods, the actual reductions being lower and apparently more realistic in the daily study.

The scatter of the estimated low flow reductions in Cathedral Peak CIII and Westfalia D (calculated using the daily flow data defined by the 70th PEL) about the original flow reduction models of Smith and Scott (1992) is shown in Figures 3 and 4, for these two catchments respectively. For CIII the modelled curve appears to over-predict the relative reduction in low flows, though the form of the curve is sound given the high variability of the data. No quantitative test of the fit has yet been performed.

**Table 1** Reductions in streamflow - total and low flows - at Cathedral Peak CIII following 87% afforestation with *Pinus patula*, calculated on data sets containing monthly flow

and daily flow values. Low flows in the monthly flow data set are those below a level exceeded 75% of the time (from Smith and Scott 1992), and in the daily flow data set are those below a level which is exceeded 70% of the time.

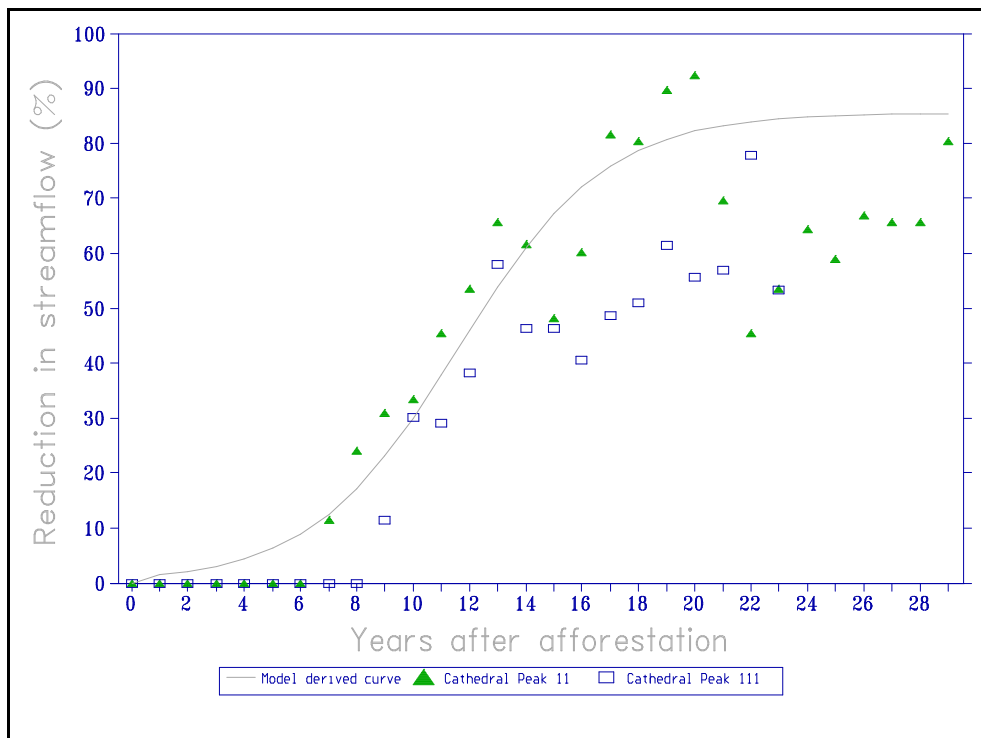
Hydrological year after afforestation		Total flow reduction			Low flow reduction		
		Monthly flows	Daily flows		Monthly flows	Daily flows	
no.	year	mm	mm	%	mm	mm	%
1	1958/9	0	0	0	0	0	0
2	1959/60	0	0	0	0	0	0
3	1960/1	0	0	0	0	0	0
4	1961/2	0	0	0	0	0	0
5	1962/3	0	0	0	0	0	0
6	1963/4	0	0	0	0	0	0
7	1964/5	0	0	0	0	0	0
8	1965/6	0	0	0	5.05	0	0
9	1966/7	30.5	106.1	11	6.14	4.87	9.8
10	1967/8	261.4	103.4	30	14.8	15.0	26
11	1968/9	153.1	108.8	21	14.6	13.9	25
12	1969/70	182.5	150.4	34	28.1	20.5	33
13	1970/1	216.2	311.7	53	10.5	11.9	50
14	1971/2	421.7	357.4	42	6.9	15.6	40
15	1972/3	521.6	226.7	48	21.6	30.4	40
16	1973/4	310.0	307.4	24	7.1	10.0	35
17	1974/5	545.7	375.0	35	28.3	22.2	42
18	1975/6	1365.5	398.0	33	18.7	22.5	44
19	1976/7	639.0	450.7	59	21.6	19.3	53
20	1977/8	614.3	440.8	45	28.2	28.1	48
21	1978/9	639.7	503.2	55	†	18.8	49
22	1979/80	685.0	342.2	70	36.5	35.7	67
23	1980/81	444.5	261.5	44	42.6	37.3	46

† Indicates a year in which no low flow events were recorded.

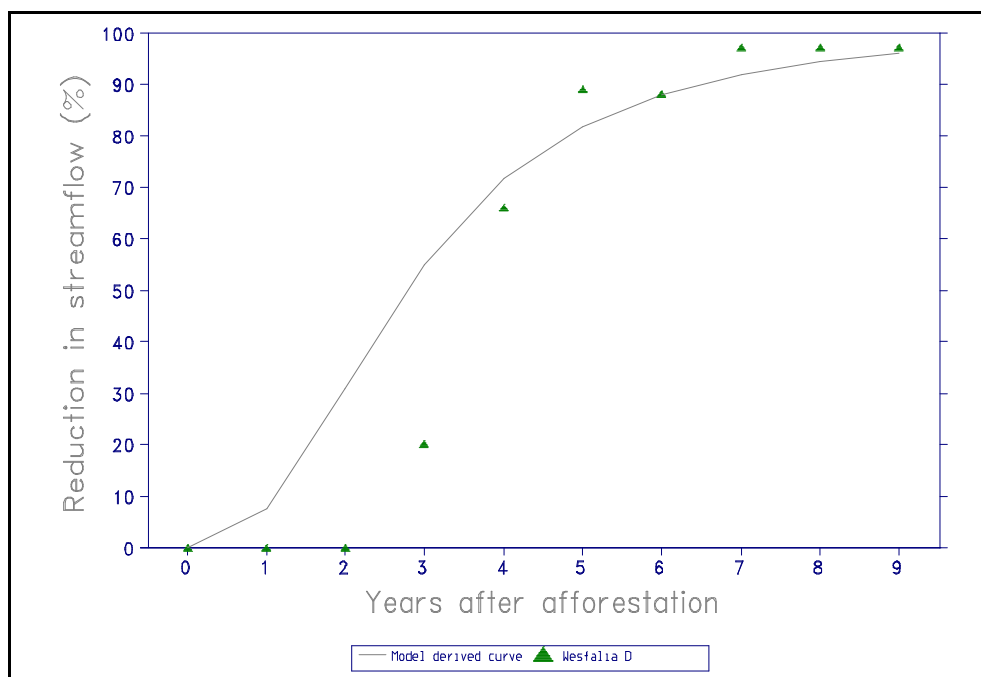
**Table 2** Reductions in streamflow - total and low flows - at Westfalia D following 100% afforestation with *Eucalyptus grandis*. The definitions of low flows are explained in the text.

Hydrological year after afforestation		Total flows				Low flows							
		Monthly flow data set *	Modelled reduction *	Daily flow data set		Monthly flow data set *	Modelled reduction *	Daily flow data sets					
								Overall 70th PEL		Mean annual 70th PEL		70th PEL in each year	
no.	year	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
1	1982/3	0	1.39	0	0	0	7.50	0	0	0	0	0	0
2	1983/4	0	9.99	0	0	0	31	0	0	0	0	0	0
3	1984/5	129.6	27	88.5	22	56.4	55	10.4	24	13.1	20	8.15	18
4	1985/6	343.0	47	251.3	61	197.2	72	16.6	63	43.9	66	40.2	65
5	1986/7	505.9	63	335.6	66	215.8	82	6.80	91	26.9	89	65.9	87
6	1987/8	648.9	75	512.6	54	119.5	88	†	-	9.52	88	83.9	82
7	1988/9	445.8	83	342.7	72	244.1	92	10.3	100	28.8	97	72.0	91
8	1989/90	502.2	88	396.3	80	162.9	94	5.11	100	32.2	97	68.7	96
9	1990/1	.	92	297.1	96	.	96	6.76	100	25.6	97	36.7	95

\* from Smith and Scott 1992;      "." indicates not calculated;      "†" indicates that no low flow occurred



**Figure 3** The scatter of low flow reductions per hydrological year following afforestation of Cathedral Peak CII and CIII (scaled up to the equivalent of 100% afforestation) about the low flow reduction curve for sub-optimal growth zones planted to pines, as proposed by Smith and Scott (1992).



**Figure 4** Low flow reduction by year following afforestation of Westfalia D, compared to the low flow reduction curve for optimal growth zones planted to eucalypts as proposed by Smith and Scott (1992).

### **The influence of the percentile exceedance level: Alternative low flow cut-off points**

In order to test the effect of the choice of the cut-off point on the results, alternative low flow levels were defined using the daily streamflow data set for Cathedral Peak CIII - one at the 50th PEL and one at 80th PEL. These corresponded to daily flow volumes of 1.0111 mm and 0.5308 mm respectively. Calibration models were determined for each of these two new data sets and reductions from the predicted streamflow were determined as for the 70th PEL (See METHODS).

The increased (50th PEL) and decreased (80th PEL) size of the data sets resulted in the actual values of flow reduction being respectively greater and smaller than those of the 70th PEL study (Table 3). Actual flow reduction values obtained in the 70th PEL study are still the closest to the values determined using the monthly data set and a 75th PEL. It is important to note that the percentage reduction in each hydrological year for the three different low flow cut-off levels are very similar, never differing by more than five percent in a single year (Table 3). One can therefore expect that the three different data sets resulting from different cut-off points (PELs) will all produce similar curves of percentage flow reduction.

At Westfalia three low flow data sets had been defined, and for each flow reductions were different (Table 2). The greater the proportion of the annual flow which is included as low flow according to the particular definition being applied, the greater absolute reduction in low flow is likely to be in that year. More significant therefore is the close agreement, as seen at Cathedral Peak, between the *percentage flow reductions* calculated using the different data sets (Table 2).

### **Low flow reductions in relation to wet and dry years**

To test the hypothesis that flow reductions are relatively greater in drought years we examined the daily low flow reductions in Cathedral Peak CIII. We looked for a direct relationship between the annual rainfall or the number of low flow days in every (hydrological) year and the reduction in streamflow from the catchment in that year. This would give an indication whether streamflow is indeed reduced to a greater extent during very dry (drought) years, compared to that of normal rainfall years.

In the first eight years after the planting of the pines at Cathedral Peak CIII there was no significant reduction in low flow attributable to afforestation. From the ninth to twentieth year the low flow reductions are progressively larger (Figures 5a & b). But the size of the relative reduction in low flow is not related to the number of low flow days nor to annual rainfall: large low flow reductions are just as likely to occur in years with a low frequency of low flow days as they are in years with a high frequency of low flow days (Figure 5a), and similarly wet years could have the same percentage reduction in low flow as dry years (Figure 5b).

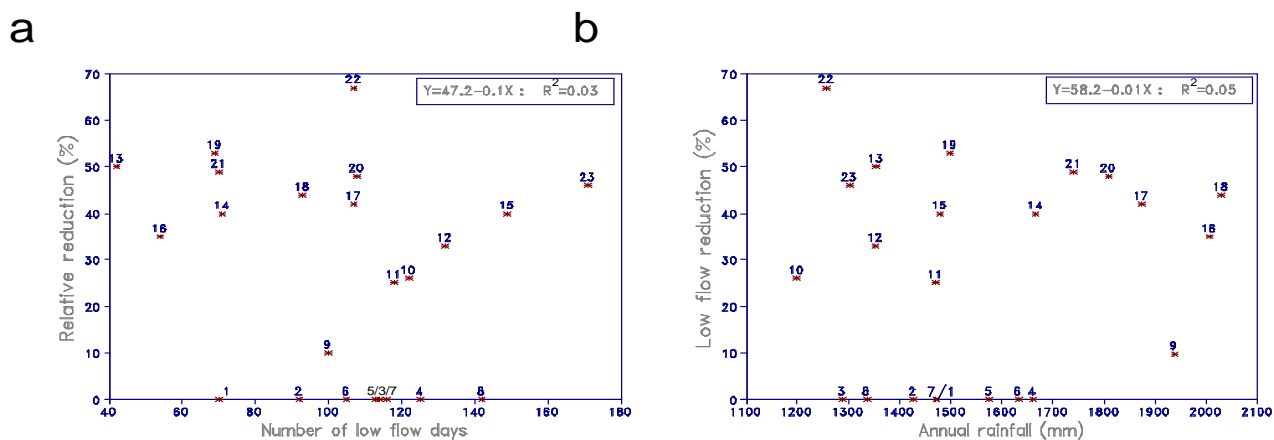


**Table 3** Comparative reductions in low flows at Cathedral Peak CIII following afforestation. Here the low flow has been defined at three different cut-off values, namely the 70th, 50th and 80th percentile exceedance levels (PEL).

Hydrological year after afforestation		Low flow reduction by hydrological year						
		Monthly flow data set *	Daily flow data set: 70th PEL		Daily flow data set: 50th PEL		Daily flow data set: 80th PEL	
no.	year	mm	mm	%	mm	%	mm	%
1	1958/9	0	0	0	0	0	0	0
2	1959/60	0	0	0	0	0	0	0
3	1960/1	0	0	0	0	0	0	0
4	1961/2	0	0	0	0	0	0	0
5	1962/3	0	0	0	0	0	0	0
6	1963/4	0	0	0	2.56	2.7	1.40	4.1
7	1964/5	0	0	0	0	0	0	0
8	1965/6	5.05	0	0	0	0	2.01	6.1
9	1966/7	6.14	4.87	9.8	11.2	11	2.45	14
10	1967/8	14.8	15.0	26	44.1	29	11.2	25
11	1968/9	14.6	13.9	25	27.9	23	7.8	24
12	1969/70	28.1	20.5	33	41.8	32	15.3	34
13	1970/1	10.5	11.9	50	73.8	53	3.2	49
14	1971/2	6.9	15.6	40	43.4	42	7.2	40
15	1972/3	21.6	30.4	40	57.6	43	18.8	39
16	1973/4	7.1	10.0	35	31.1	38	5.8	37
17	1974/5	28.3	22.2	42	40.1	40	14.3	43
18	1975/6	18.7	22.5	44	39.6	40	8.5	45
19	1976/7	21.6	19.3	53	46.1	52	10.2	55
20	1977/8	28.2	28.1	48	46.0	46	10.6	48
21	1978/9	†	18.8	49	62.5	50	5.5	47
22	1979/80	36.5	35.7	67	79.2	68	19.5	66
23	1980/81	42.6	37.3	46	53.5	44	27.1	47

\* Low flow reductions calculated using the monthly flow data set and a 75th percentile exceedance level (Smith and Scott 1992).

† Indicates a year in which no low flow events were recorded.



**Figure 5** The reduction in low flow (%) for each post-afforestation year (age shown above each data point) plotted against the number of low flow days in each hydrological year (a) and against annual rainfall (b). The simple linear regression does not include years 1-8.

### Verification on an independent catchment

The predictive ability of the flow reduction curve for pine on sub-optimal growth zones was tested by using an independent catchment, i.e. one that had not been used in developing the Smith and Scott (1992) flow reduction models. The best catchment at our disposal for this purpose was CII at Cathedral Peak. This grassland catchment was afforested to *Pinus patula* in 1951 and clearfelled progressively from 1981.

The streamflow reduction as a result of afforestation in CII was statistically significant in the sixth year after planting, two years earlier than in CIII, and seemed to increase more sharply than those in CIII. But from the tenth year, the reductions in low flow in CII are comparable to those in CIII for the same age after planting (Figure 1). It is also obvious from Figure 1 (and Table 1) that there is considerable year to year variation in the percentage reduction in flows, but overall the effects of afforestation on low flows is little different from that on total flow (Table 1).

The low flow reductions measured at Cathedral Peak CII match quite closely (Figure 1) the modelled low flow reduction curve of Smith and Scott (1992). There is a sudden decrease in the size of the flow reductions in CII at about 21 years after afforestation, an effect which lasts about four years (Figure 1). This dip is attributed to the invasion of a moth (*Euproctis terminalis*)

which defoliated roughly 25% of the plantation in 1971 (Bosch 1979). The infestation lasted until 1975, 24 years after afforestation. This decrease in canopy density probably led to a reduction in evaporation from the plantation until the canopy had recovered.

## Conclusions

- 1.The percentage reduction in low flows calculated using daily flow as the computational unit is practically the same as that calculated using monthly flow data.
- 2.Similarly, it appears that the shape of the flow reduction curve (modelled) will change very little if the exceedance level according to which low flow is defined is changed from the 50th to 80th percentile. As the low flow data set is increased in size so it can be expected that the relative effect of afforestation on these low flows will approach the effect of afforestation on total flow.
- 3.A re-analysis of data confirms that the effects of afforestation on total flow are not very different in individual years from the effect on low flows. This is particularly the case where the crop is pine in a sub-optimal growth zone such as Cathedral Peak. The difference is greater under fast-growing eucalypts. Also, the accumulated difference over a whole rotation could be higher than is immediately apparent from inspection of the total flow and low flow models.
- 4.There is no evidence to support the hypothesis that the relative reductions in low flow caused by afforestation are greater in drought years than in other years.
- 5.The results of this study generally support the total and low flow reduction curves proposed by Smith and Scott (1992).

## Acknowledgements

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