Effect of clearfelling pines on water yield in a small Eastern Transvaal catchment, South Africa

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Abstract

A catchment afforested partially with exotic pines in the Witklip experimental catchment area near White River in the Eastern Transvaal (South Africa), was clearfelled to test the effects of deforestation on catchment water yield. Water yield is an important issue in the Eastern Transvaal as the highest percentage of afforestation in South Africa takes place in this area and it is also an area of intense competition for water resources. The effects of treatment were assessed using the paired catchment approach. Simple regression analysis results revealed that clearing the forest led to a significant increase in catchment water yield of approximately 280 mm/a (S.E. ± 55.4) during the first 4 years after completion of treatment. Maximum seasonal streamflow increases were approximately 250 mm/a during the high-flow period (summer) and 140 mm/a during the low-flow period (winter). The results from this study are in accordance with results obtained in several other catchment studies world-wide, verifying results from other parts of the world under South African conditions.

Introduction

The reduction in streamflow caused by afforestation affects water use downstream and has led to disputes between timber growers and other farmers during past dry cycles, when streamflow has been insufficient for normal production needs. This world-wide problem has stimulated research on the effects of afforestation on catchment water yield. It has since been demonstrated in numerous studies world-wide, that clearing forests from catchments generally increases streamflow (Hibbert, 1967; Nakano, 1967; Bosch and Hewlett, 1982; Troendle and King, 1987, Borg *et al.*, 1988; Cheng, 1989). Bosch and Hewlett (1982) summarised 94 catchment experiments and concluded that an average increase of approximately 40 mm/a per 10% cover reduction could be expected from clearfelling pine and eucalypt stands. In South Africa, afforestation, the reverse of clearfelling, has been extensively researched (Wicht, 1967; Nänni, 1970; Bosch, 1979; Van Lill *et al.*, 1980; Van Wyk, 1987). Maximum reductions in annual streamflow, following afforestation of natural grassland or fynbos, were in the order of 300 mm. These reductions are, however, relative to average streamflow from catchments with a stable natural vegetation cover. Deforestation on the other hand, leaves the ground bare for a period of time before re-establishment. One would therefore expect the increase in annual streamflow after deforestation to be larger than the maximum reduction in annual streamflow after afforestation, simply because the difference in transpiration between two vegetation types is expected to be smaller than that between one vegetation type and no ground cover (as is the case after clearing). Bosch and Von Gadow (1990) assume this to be the case in their discussion on the implications of plantation management rotation on catchment water yield. This assumption would only be valid if evaporation (from the bare soil) is lower than the transpiration component of vegetation. This assumption, however, needs to be verified.

This experiment was laid out as a paired catchment experiment, which on a catchment basis, is still considered to be the best method for analysing the effect of treatment on streamflow because it compensates for the effects of external influences like differences in vegetation and climate (Hewlett and Pienaar, 1973). The hypothesis tested is that the clearing of a pine plantation will cause an increase in streamflow. It is anticipated that results obtained in other parts of the world may be verified for South African conditions.

Experimental area

A paired catchment experiment was laid out in the Witklip State Forest, close to White River in the Eastern Transvaal, South Africa (latitude 25° 14′S and longitude 30° 53′E). The Witklip catchments form part of the Eastern Drakensberg escarpment, which has a humid, subtropical climate. Mean annual precipitation is 1 475 mm with a minimum of 1 054 mm and a maximum of 1 921 mm for the period 1974 to 1987. The indigenous vegetation is a North Eastern Mountain sourveld, and comprises short grassland with forest remnants in the sheltered valleys, and gallery forest on the escarpment with a shrub ecotone. A detailed description of the area is given by Wicht and Kluge (1976).

The Witklip catchment experiment comprises 8 small catchments (Fig. 1), gauged with compound, V-notch, sharp-crested weirs since 1975, and a rain gauge network of Casella recording gauges (recording on a weekly basis) and standard non-recording Snowden rain gauges (with nipher shields). The position of the weirs and rain gauges are indicated in Fig. 1. Measurements of temperature, humidity, hours of sunshine, wind and evaporation are taken at the central weather station (Fig. 1). Catchment III is used as a control in this analysis, and only the effects of treatment (deforestation) on Catchment V are dealt with in this paper. Treatments carried out in the other catchments will be dealt with in separate studies.

The north-facing Catchment III (control catchment) covers an area of 159 ha, of which 104,8 ha comprises indigenous vegetation and 54,2 ha comprises pine plantation *(Pinus elliottii* and *P. patula)* and eucalyptus fire belts *(Eucalyptus paniculata, E. maculata, E. albens)*, most of which were planted in September 1948. Rainfall is gauged at the upper and lower ends of the catchment. Monthly rainfall for Catchment III, calculated from the average of the two gauges, is illustrated in Fig. 2.

The north-westerly facing Catchment V covers an area of 108 ha, of which 56,3 ha is under exotic plantations and 51,7 ha of the catchment comprises indigenous vegetation (grasslands on the slope and indigenous scrub in the riparian zones). Ninety four per cent of the planted area was established between March 1942 and April 1943 and the remaining area in June 1955. Most of the exotic plantations of Catchment V were eventually clearfelled (treatment) and the various species present within the catchment, along

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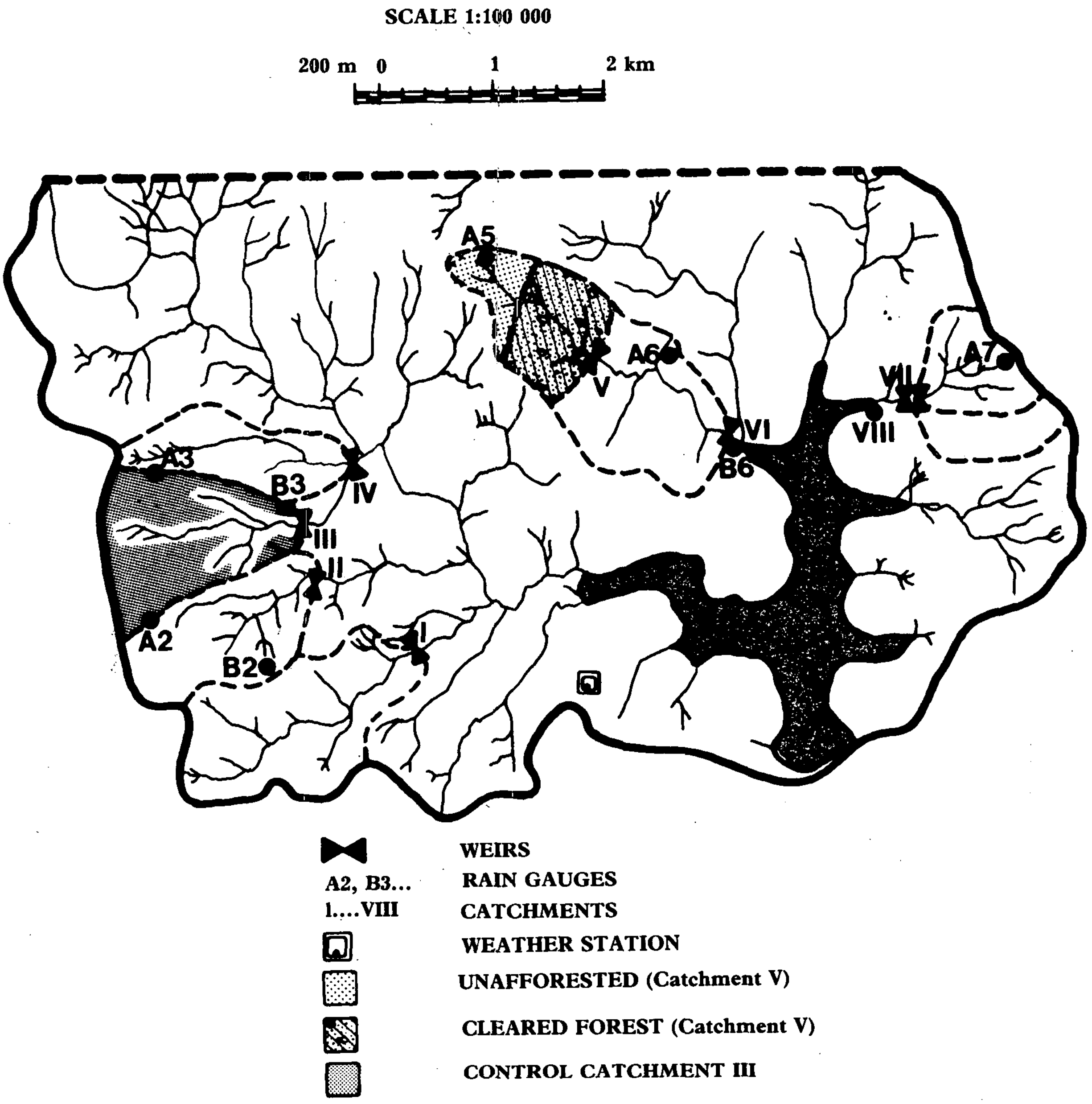

Figure 1
The eight research catchments at Witklip State Forest, illustrating the positions of the streamflow-gauging weirs and rain gauges in the treated (Catchment V) and control (Catchment III) catchments as well as the position of the central weather station

with their respective areas, planting dates and clearfelling dates are given in Table 1.

Method

The paired catchment approach of Hewlett and Pienaar (1973) was used for the experiment. It is based on the assumption that the relationship between the streamflow of two physiographically similar catchments will remain the same, should the vegetation of these catchments remain the same or change in a similar fashion. At least two catchments (control and treated catchments) and two time periods (the calibration and the treatment periods) are involved. The period during which the vegetation remained unchanged in both catchments, is referred to as the calibration period. During the calibration period (August 1975 to June 1980), monthly streamflow totals from Catchment V (to be treated) were regressed against that of Catchment III (control). After treatment, any effect is illustrated by the deviations in streamflow between the derived calibration estimates and the real flow measurements.

Different statistical models using simple regression analyses procedures (PROC REG in SAS; SAS inc., 1985) were tested to determine the best calibration relationship between the monthly streamflow totals of the two catchments. The derived model enables predictions of streamflow for Catchment V to be made from that of Catchment III had no treatment been applied. Any deviations in streamflow during the post-treatment period (July 1980 to February 1986) from these predicted values, are taken to show changes resulting from the treatment. These deviations were expressed as a monthly time trend and later quantified to determine the effect of treatment. Data were adjusted to account for the par-

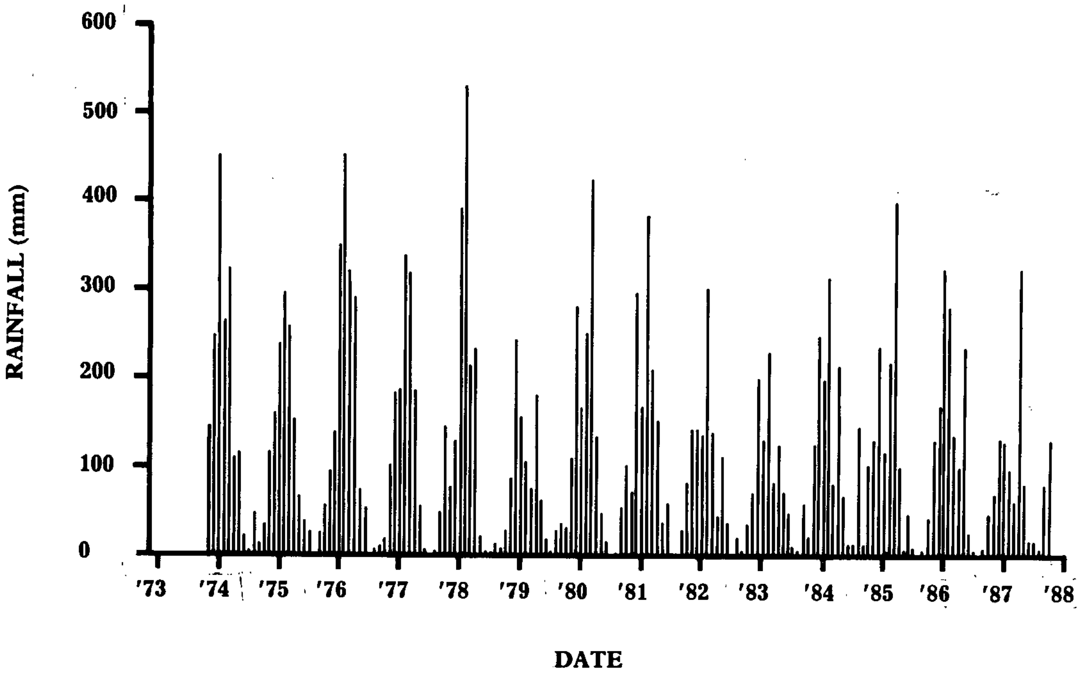

Figure 2
Monthly rainfall for the experimental period taken as the average of the rainfall measured at the two rain gauges in Witklip Catchment III

TABLE 1
THE PLANTING AND FELLING SCHEDULE FOR CATCHMENT V

Vegetation	Species	Area (ha)	Area (%)	Planted	Clearfelled
Pine forest	*Pinus patula*	9,7	8,98	Apr 1943	Jun 1980-Nov 1980
	P. roxburghii	2,3	2,13	Mar 1942	Mar 1982-Aug 1982
	P. patula	17,9	16,57	Mar 1942	Jan 1982-Nov 1982
	P. patula	13,9	12,87	Apr 1943	Feb 1983-Apr 1983
	P. patula	3,0	2,78	Jun 1955	Feb 1983-Apr 1983
Total area		46,8	43,3		
Eucalyptus (firebelt)	*E. saligna*	2,4	2,22	Apr 1943	Jun 1981
	E. paniculata	4,7	4,35	Apr 1943	Jun 1984
	E. paniculata	2,4	2,22	Apr 1943	Jun 1983
Total area		9,5	8,79		
Total plantation		56,3	52,13		
Grassland/indigenous scrub		51,7	47,87		
Total		108	100		

tial clearing of the catchment by dividing streamflow deviations (volumes) resulting from treatment by the proportion of the catchment that was cleared rather than by the entire catchment area.

The effect of treatment on high (during summer) and low (during winter) period flows was also investigated. High period flows were taken to be monthly streamflow totals greater than 15 mm, and those below 15 mm were taken to be low-flow periods. Calibration models were derived for low- and high-flow classes separately.

Models were also fitted to the peak- and stormflow (direct runoff component of streamflow) data to determine the effect of treatment on the magnitude of these events. The stormflow data was digitised from streamflow charts produced by Belfort water level recorders. All storm events from 4 years, 2 during the calibration period and 2 post-treatment, were analysed, and the storm- and peakflow data from each storm in Catchment V were regressed against the same storms in Catchment III during the calibration period. The deviations from the predicted values were plotted and

TABLE 2

MODEL PARAMETERS AND STATISTICS OF THE STREAM-, PEAK- AND STORMFLOW ANALYSES

Type of model	Model	Intercept	Regress. coeff.	F	P>F	R^2
1. Monthly flow	$\ln(Y)=\ln(a)+b(\ln(X))$	-1,59	1,25	441,6	0,0001	0,89
2. Low monthly flow (< 15 mm)	$\ln(Y)=\ln(a)+b(\ln(X))$	-1,06	1,02	42,9	0,0001	0,60
3. High monthly flow (> 15 mm)	$\ln(Y)=\ln(a)+b(\ln(X))$	-0,24	0,95	130,2	0,0001	0,83
4. Monthly stormflow	$\ln(Y)=\ln(a)+b(\ln(X))$	-0,11	0,74	77,94	0,0001	0,78
5. Monthly peakflow	$\ln(Y)=\ln(a)+b(\ln(X))$	0,04	0,98	63,07	0,0001	0,74

Y = flow (mm) from Catchment V (treated catchment)
X = flow (mm) from Catchment III (control catchment)
a,b = regression coefficients

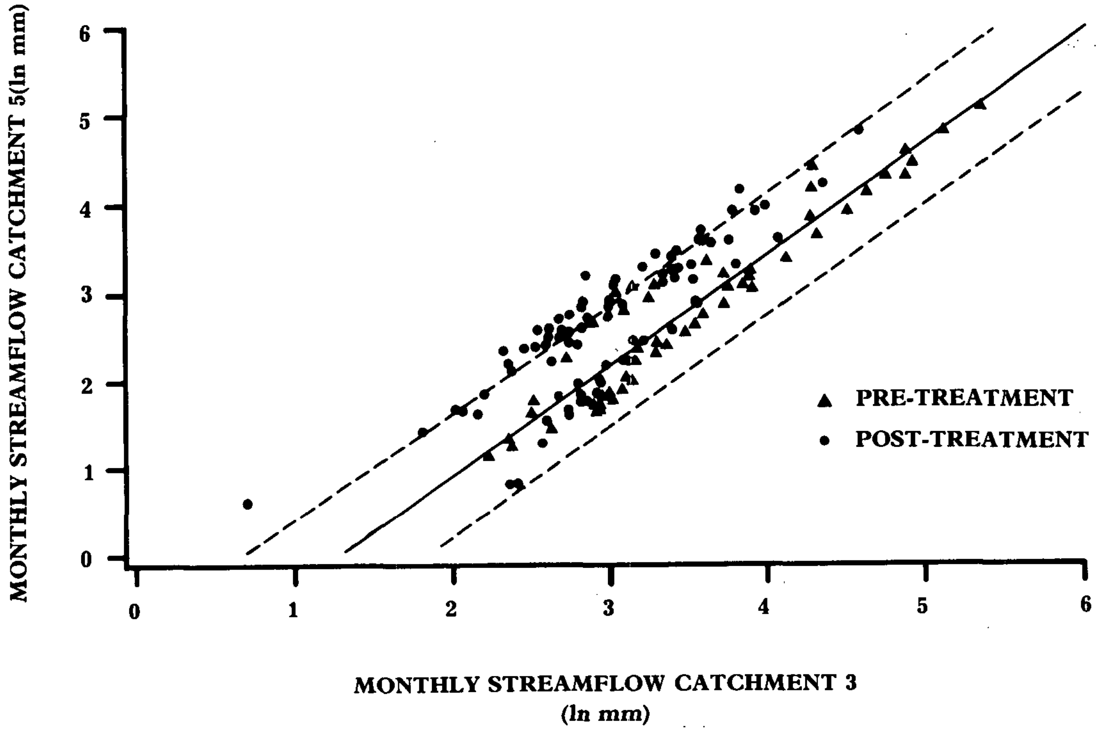

Figure 3
Calibration period regression line between the monthly streamflow of the control and treated catchments, with the 95% confidence limits (stippled) and the pre-(triangle) and post-treatment (circle) observed flows

quantified to establish the effect of the clearfelling treatment. The response factors (percentage of precipitation that appears immediately as stormflow) for both catchments were also determined.

Dummy variables of 0 and 1 were assigned to the calibration and treatment periods to test the significance of the changes due to treatment during the first 5 hydrological years after trreatment (Gujarati, 1978). Hydrological years refer to the period between October of one year and September of the next. They are used in preference to calender years in the summer rainfall regions to compensate for the lag effect of streamflow response to rainfall (with most rainfall in this region falling between November and March). A full model with treatment as a variable was compared to a reduced model without treatment as variable, and then an F-test was applied to determine whether the model with treatment accounted for a significantly greater proportion of the sum of squares than the reduced model.

Results

A log-linearised regression model (parameters and statistics in Table 2) best predicted streamflow changes due to treatment. The model with its 95% confidence limits and the pre- and post-treatment observed flows are illustrated in Fig. 3. The distribution of monthly streamflow residuals (log) from the modelled streamflow during the calibration period is illustrated in Fig. 4 and the deviations in streamflow of Catchment V from the model predictions are illustrated in Fig. 5. Large positive deviations are apparent after the clearing of Catchment V, illustrating the increase in

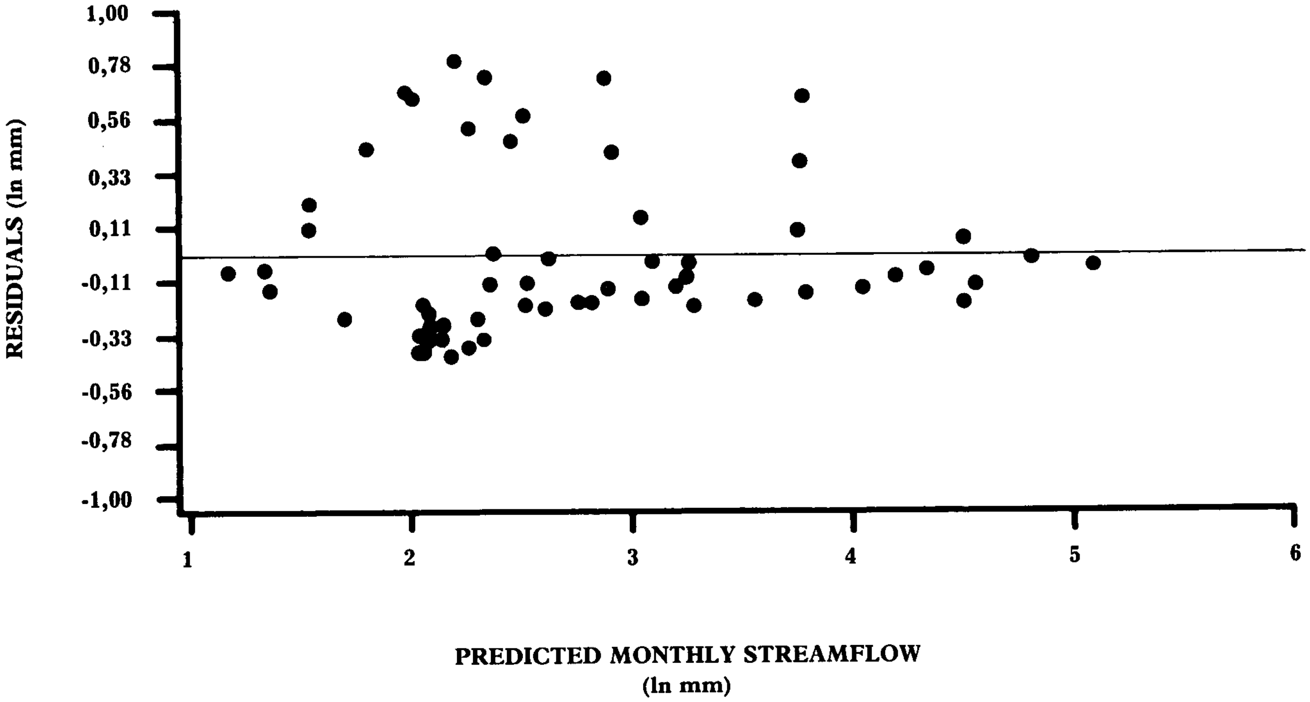

Figure 4
The deviations in observed streamflow (in log units) from the model-predicted monthly streamflow values for the calibration period

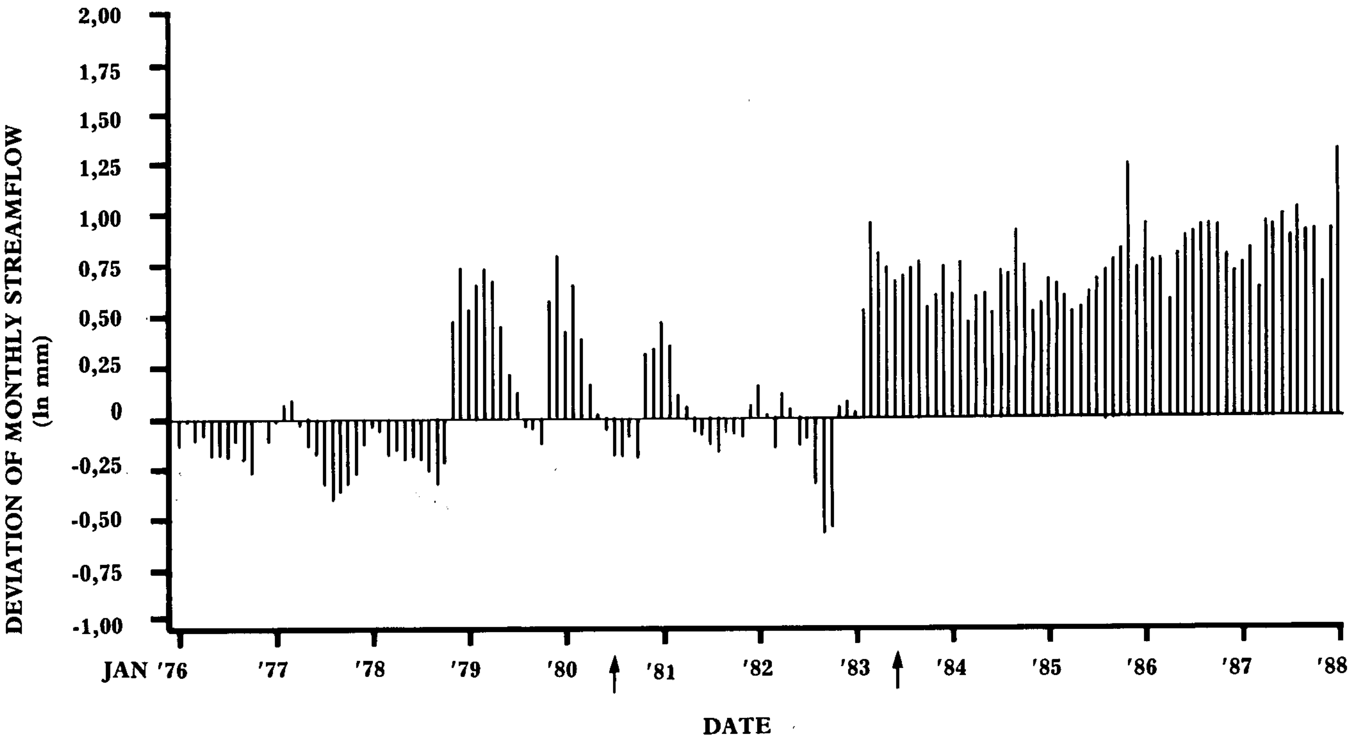

Figure 5
The deviations of monthly streamflow (vertical bars) in Catchment V from the model predicted values (ln (Y)= ln(-1,59) + 1,25 (ln X)) (the period over which the catchment was cleared falls between the two arrows)

TABLE 3
CHANGES IN CATCHMENT WATER YIELD AFTER DEFORESTING CATCHMENT V

	Oct 82-Sep 83	**Oct 83-Sep 84**	**Oct 84-Sep 85**	**Oct 85-Sep 86**	**Oct 86-Sep 87**
Change in streamflow (mm/a) relative to model estimate	66,0	200,8	331,9	416,8	184,3
Change in average monthly streamflow (mm) relative to model estimate	5,5	16,7	27,7	34,7	15,4
Change in streamflow (mm/a) beyond 95% confidence limits of model estimates	21,1	13,2	3,8	102,8	49,5
Changes in seasonal low flow (mm) relative to model estimates	50,5	37,3	41,6	31,6	140,5
Change in seasonal high flow (mm) relative to model estimates	12,0	83,3	207,3	250,6	28,2
Calculated F value and tabulated F value (brackets)	6,5(4,7) **	19,3(4,7) **	19,6(4,7) **	36,5(4,7) **	30,6(4,7) **

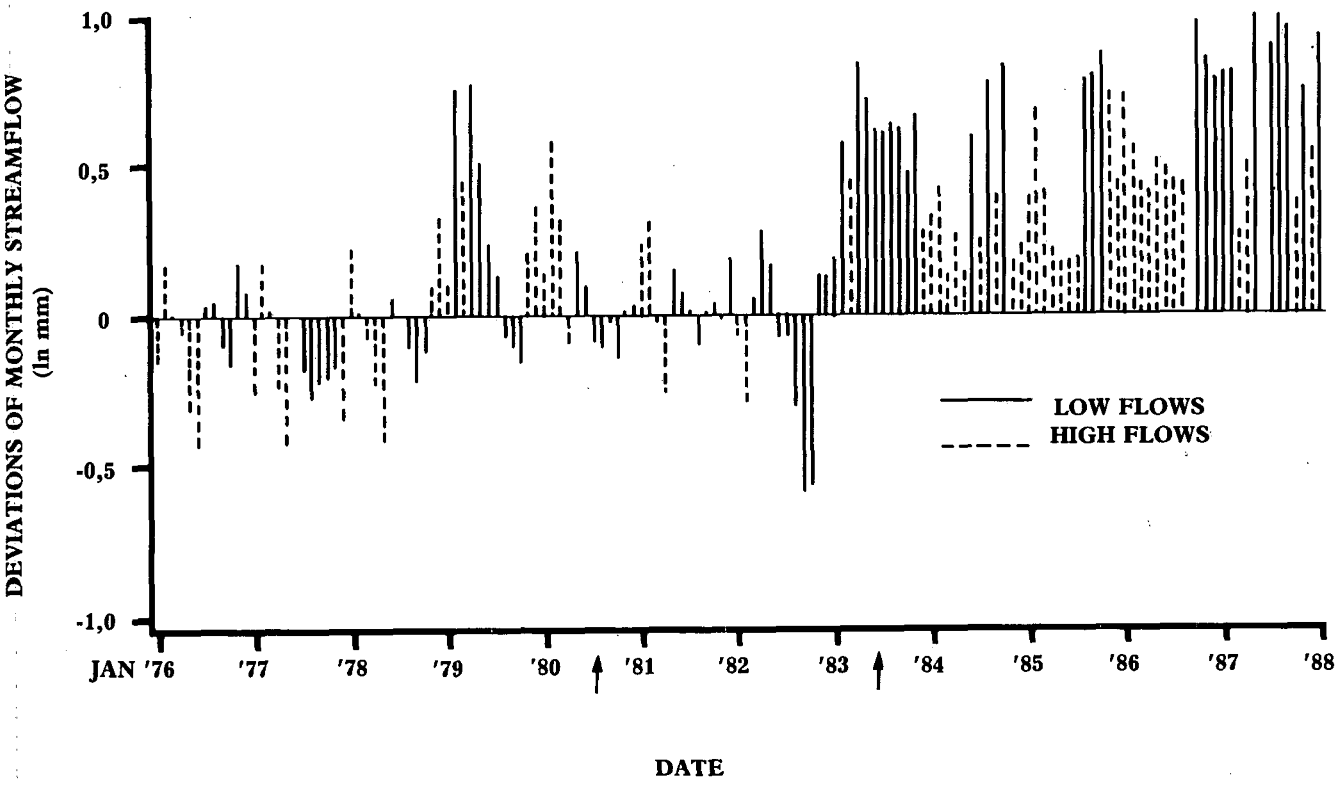

Figure 6
The deviations of monthly high flows (stippled vertical line) and low flows (solid vertical line) in Catchment V from the model predicted values (the period over which the catchment was cleared falls between the two arrows)

monthly streamflow after treatment. The calculated increases in streamflow following deforestation are given in Table 3.

The relationships between the catchments for seasonal low flows (model 2, Table 2) and high flows (model 3, Table 2) were also exponential (as for model 1, Table 2) and therefore the data were transformed (log transformation) to linearise them for the regression analysis. The deviations in high and low flows of Catchment V from the model predictions are illustrated in Fig. 6, with high deviations in both seasons after the treatment period indicating the effect of treatment. The calculated increases in low and high period flow following deforestation are given in Table 3. The baseflow recession rate was much faster in the treated catchment than for the control, possibly explaining the relatively low R^2 value for the low-flow data.

The clearing of the catchment had a significant effect on water yield, increasing annual streamflow yield by 66,0 mm during the first hydrological year post-treatment (October 1982 to September 1983). This first year was not, however, entirely free of treatment as can be seen from Table 1. During the next 4 hydrological years after treatment, the increases were 200,8 mm, 331,9 mm, 416,8 mm and 184,3 mm respectively (Table 3). During the period June 1980 (when treatment commenced) to September 1982 (when 30% of the catchment had been cleared), there was no significant increase in streamflow. Treatment caused a significant increase in both high and low flows. Increased low flows ranged from approximately 30 to 140 mm during the first 5 years after treatment. High flows increased from 12 mm during the first year to 250 mm in the fourth year, and then declined to 28 mm during the fifth year. Rainfall during the first and fifth years years after treatment was markedly lower than the mean annual rainfall, accounting for the low increases in high-flow data during these two years, with periods of low rainfall logically having a greater influence on high flows than on low flows.

Log-linearised regression models (Table 2) were also used to best describe the calibration relationship between Catchments III and V for all peak- and stormflow events. The clearing of the catchment resulted in a significant but slight decrease in peak- and stormflow values of 0,04 and 0,14 mm respectively. The streamflow response (amount of rainfall that appears immediately as streamflow) factors for Catchments III and V were 0,020 and 0,018 respectively, indicating that a very small percentage (2%) of precipitation appears immediately in the form of streamflow or spate flow.

The F-test (Table 3) showed a significant contribution of the dummy variables representing treatment to the reduced model at a 1% level for each year after treatment.

Discussion

Clearing the pine plantation of Catchment V had, as expected, a significant effect on catchment water yield at Witklip. The increase was generally in the order of 280 mm/a (S.E. ± 55,4) from October 1983 to September 1987, similar to results from studies in other parts of the world (Bosch and Hewlett, 1982). The partial clearing of Catchment V led to an increase in streamflow of approximately 50 mm/a for every 10% of cover reduction, which is slightly higher than Bosch and Hewlett's (1982) predictions. One of the reasons for the lower streamflow increase during the first hydrological year (66 mm/a) was probably due to only 30% of Catchment V having been cleared at this stage. Rainfall figures during the last year of treatment (1982) and during the first year after treatment (1983) were well below the mean (1 475 mm), being 1 115 and 1 054 mm/a respectively. This may be another reason for the small streamflow response to clearing during this first year after treatment, as streamflow response depends quite strongly on mean annual precipitation (Bosch and Hewlett, 1982). The low rainfall may have caused a delay in the streamflow response to treatment, with much of the rainfall during these years being absorbed to recharge ground-water resources. This may also have been the reason for the decline in the magnitude of streamflow increase during the fifth hydrological year after treatment (rainfall during this year being 1 163 mm). At the mean precipitation level of *ca.* 1 470 mm/a (as for Witklip), the expected increase in streamflow following deforestation for Witklip would be *ca.* 200 mm/a if the catchment had a 100% cover reduction (Bosch and Hewlett, 1982). Only 52% of Witklip's Catchment V was cleared of pines, however, and therefore it was expected that the increase in catchment water yield following treatment would probably be lower than 200 mm/a for Catchment V. The actual increase in streamflow from Catchment V was therefore larger than what would have been predicted.

One of the problems associated with deforestation experiments in the eastern part of the country is the vigorous regrowth of the understorey of weed species (e.g. *Solanum mauritianum, Psidium guayava)* or indigenous vegetation due to the subtropical climate of the region. It is extremely difficult to assess what quantities of water are used by the rapidly recovering regrowth. Additionally, the clearing of the catchment also took place over a period of almost 3 years, and therefore, in parts of the catchment, the newly planted trees were already 3 years old by the time the entire catchment was finally cleared. Van Lill *et al.* (1980) showed that pine plantations start exerting an observable influence on streamflow after approximately 3 years. The understorey would also have been well-established by then. These newly planted trees probably use substantial quantities of water during their juvenile growth period, confounding the effects of clearing of the catchment. Water yield after treatment may have been substantially greater had conditions been more ideal. Unfortunately, foresters are bound to clearfell at rates which satisfy the timber demand and sawmill capacity (rather than saturate the market). This highlights some of the problems associated with deforestation experiments, and possibly explains why few experiments of this nature have been undertaken.

There has been considerable debate and controversy concerning the effects of deforestation on peak- and stormflow values. Deforestation has, in some cases, increased stormflow and/or peakflow values significantly (Nakano, 1967; Hewlett and Helvey, 1970; Hornbeck, 1973; Harr *et al.,* 1975). Hewlett and Bosch (1984), in their analysis of stormflow data from 8 small catchments in South Africa, found that afforestation had an unimportant effect on stormflow volumes and a small but significant effect on peakflow rates. The data were obtained from catchments that had been converted from a natural stable state to a plantation of exotic trees. The marginal decrease in peak- and stormflow in this experiment was rather surprising, in that if anything, an increase was expected. These decreases were, however, very small, and will probably have a negligible effect on the catchments. The response factors for both Catchments III and V compared well with data from several other South African catchments, although being lower than the average response factor of 3,4% for these catchments (Hewlett and Bosch, 1984) and exceptionally low in comparison with the average of 20% for eastern USA catchments (Hewlett, 1982). Both Catchments III and V have relatively shallow basins and their hydrologic responses compared well with other catchments of similar steepness (e.g. Bosboukloof and Mokobulaan; Hewlett and Bosch, 1984). Catchment III has a slightly steeper basin than Catchment V, accounting for the slightly higher response factor.

Conclusions

Partial clearing (52%) of the pine plantation in Catchment V at Witklip over a period of 4 years has caused a significant increase in catchment water yield, equalling or exceeding the expected increase for a partial clearing of the catchment. The long treatment period and the very dry post-treatment period are factors that confound the analyses, however, and even greater increases in streamflow may well have occurred, had experimental conditions been more favourable. The results of this study support the assumption that streamflow increases following deforestation are usually greater than streamflow decreases after afforestation. Quantification of the water used by the rapidly recovering understorey in these subtropical regions after deforestation will also facilitate the interpretation of deforestation experimental results.

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