Some effects of afforestation on streamflow in the Western Cape Province, South Africa

DB van Wyk

Jonkershoek Forestry Research Centre, South African Forestry Research Institute, Private Bag X5011, Stellenbosch 7600, South Africa.

Abstract

This paper reports results of a multiple catchment experiment in the South Western Cape Province of South Africa where the influence of afforestation with *Pinus radiata* on streamflow was monitored from 1940 to 1980. Afforestation resulted in reduced streamflow. In the case where 98% of the catchment was afforested streamflow decreased by 313 mm from an initial 663 mm to an average of 350 mm/a over a period between 12 and 32 years after afforestation. Streamflow stabilised at this level. In the catchment with 57% afforestation, streamflow declined by 200 mm/a from an initial 593 mm/a over the period 16 to 40 years after afforestation. Here streamflow stabilised at about 20 years. Percentage of area afforested, total biomass and rainfall appear to have influenced the magnitude of reductions in streamflow.

Introduction

The Jonkershoek Forest Research Centre (18°15'E and 33°57'S) was established in 1935. Investigations were planned to find ways of safeguarding and, if possible, improving water supplies, and of reducing floods. The research was also intended to resolve the controversy as to whether extensive timber plantations of exotic tree species, which replace natural grass or shrubveld, affect streamflow adversely. Preliminary results from these experiments indicated that afforestation with pines resulted in significantly reduced streamflow (Wicht, 1967b; van der Zel and Kruger, 1975; and van Wyk, 1977). Wicht (1967a) has reviewed the history of forest hydrological research in South Africa.

This study aims to update the initial estimates by analysing data for a full 40 year afforestation cycle from planting to clear-felling of one catchment, Bosboukloof, which forms part of a

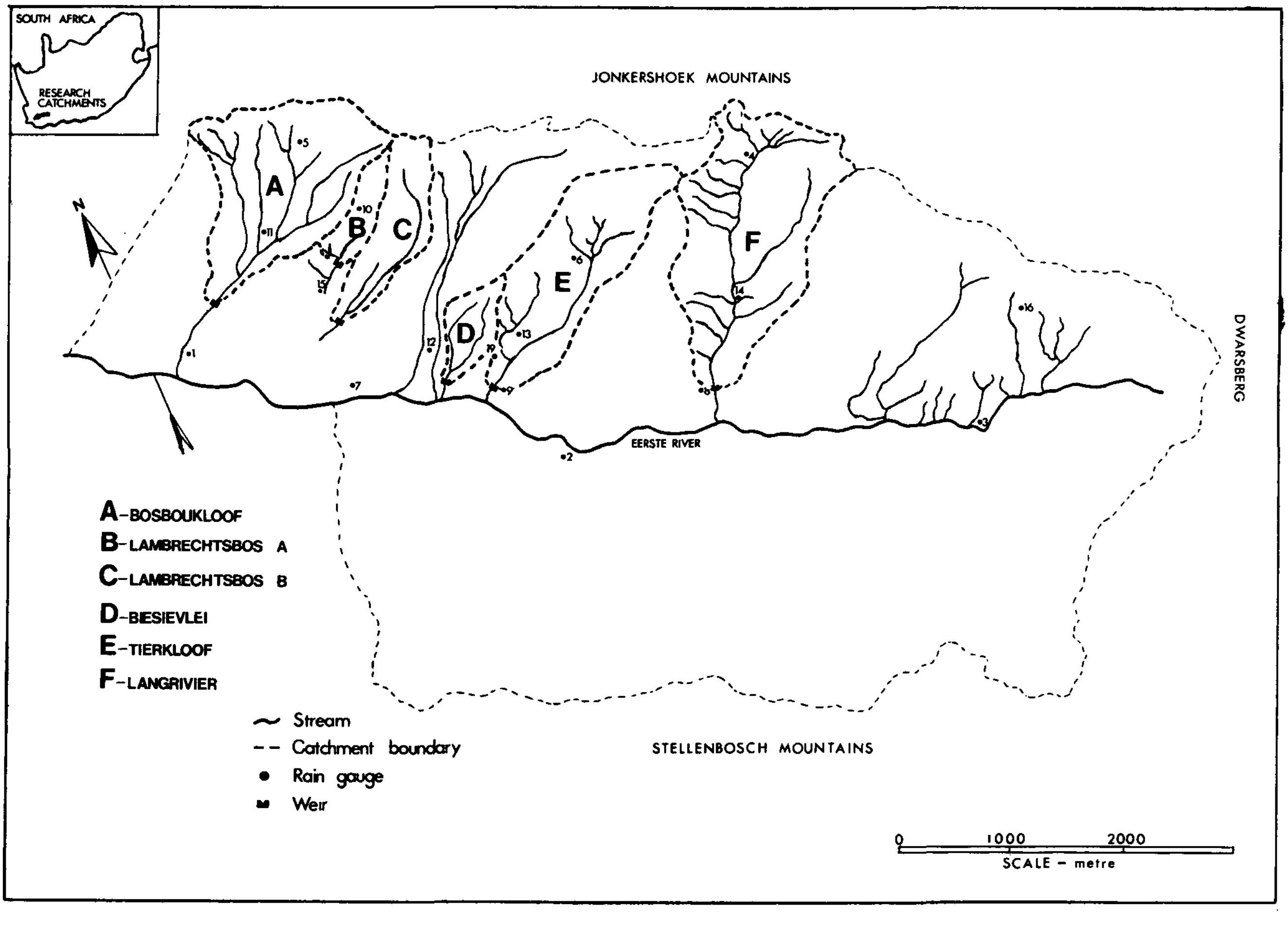

Figure 1
Map of the Jonkershoek research catchments, mountains and raingauges.

Received 14 March 1986.

TABLE 1
PHYSICAL FEATURES OF THE JONKERSHOEK EXPERIMENTAL CATCHMENTS

Catchment name	Area (ha)	Percentage afforested	Mean elevation (m)	Mean slope %	Aspect	Age of trees in years					
						Year					
						1940	1948	1956	1964	1972	1980
Bosboukloof	200,9	57	543	26	S.W.	0	8	16	24	32	40/0*
Biesievlei	27,2	98	396	23	S.W.	X	0	8	16	24	32
Tierkloof	157,2	36	900	49	S.W.	X	X	0	8	16	24
Lambrechtsbos B	65,5	82	660	46	S.W.	X	X	X	0	8	16
Lambrechtsbos A	31,2	89	690	45	S.W.	X	X	X	X	0	8
Langrivier	245,8	—	950	40	S.W.	X	X	X	X	X	X

X – Protected (fynbos)
0 – Afforestation (*Pinus radiata*)
* – Clearfelling

multiple catchment experiment. This experiment also includes Biesievlei, Tierkloof, Lambrechtsbos A and Lambrechtsbos B and Langrivier as the unafforested control.

Study area

The layout of the experimental catchments at Jonkershoek, (Bosboukloof, Biesievlei, Tierkloof, Lambrechtsbos A, Lambrechtsbos B and Langrivier) and the physical features of the research area are presented in Figure 1 and Table 1. The Jonkershoek valley is enclosed on three sides by mountains which range in elevation from 792 to 1 525 metres. The open side of the valley is to the north-west, from which direction the prevailing rain-bearing winds blow. The research area thus has a steep rainfall gradient increasing towards the Dwarsberg at the head of the valley to the south-east. The Dwarsberg is one of the sites with the highest recorded rainfall in the country (mean 3 600 mm/a).

The climate is mediterranean, and rainfall is the predominant form of precipitation. About 85% of the rain falls in the six months from April to September. There is a considerable natural variation in the annual rainfall to runoff ratio. This is illustrated in Figure 2 which gives streamflow and rainfall for the protected fynbos catchment Langrivier. Winter temperatures are not cold enough to induce a marked rest period in the growth of the exotic plantation trees (*Pinus radiata*) (Van Laar, 1967). Based on 30 years data from the central meteorological stations the mean annual temperature is 16,1°C with a yearly maximum 38,1°C and minimum, 0,7°C (Van Lill, 1976). According to Thornwaite's classification it is a humid-mesothermal forest climate with a P/E index, I, of 103,2 and a thermal efficiency factor, i, of 86,7 (Wicht *et al.*, 1969).

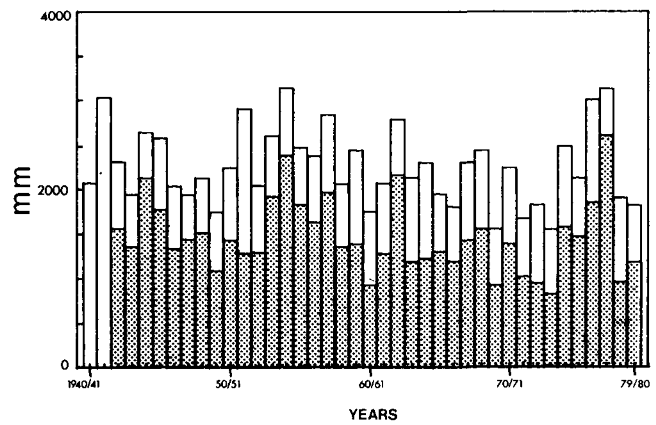

Figure 2
Mean annual rainfall (unshaded) and annual runoff (shaded) for Langrivier.

The natural vegetation of the area is a tall (2 to 3 m) open to closed shrubland (*vide* Campbell *et al.*, 1981) dominated by *Protea neriifolia*, *Protea repens*, *Brunia nodiflora* and *Widdringtonia nodiflora*. Evergreen tall forests (> 10 m) dominated by *Ilex mitis* and *Cunonia capensis* occur on suitable sites along permanent streams (Van Wilgen, 1982).

The geology comprises sandstones of the Table Mountain Group (Cape Supergroup) which are underlain by Cape Granite. A shale band runs through the sandstone and small lenses of shale occur irregularly. Sandstone colluvial material is common throughout. The soils are derived from these strata and sandstone debris and granite boulders form a colluvial admixture on the granite floor of the valley. The major soil forms are Hutton, Magwa and Nomanci (Macvicar and de Villiers, 1977). The soils are loams to sandy loams with a low bulk density which varies between 0,9 and 1,3. They are friable presenting excellent conditions for infiltration (Versfeld, 1981).

Methods

Experimental design

The experimental layout is a multiple catchment experiment (Wicht, 1967a). Five catchments were planted with *P. radiata* at eight year intervals (see Table 1). The percentage afforestation of each catchment varied from 98% to 36%. The pines were planted at an initial espacement of 2,7 × 2,7 m (1 330 stems/ha). Stands were thinned three to four times over 30 years to a final density of 150 to 175 stems per ha depending on site quality. The fynbos vegetation on the sixth (control) catchment, Langrivier, was burnt accidentally in 1942 and has been protected from fire since then. After the afforestation of Bosboukloof (one of the catchments), the fynbos in the remaining catchments Biesievlei, Lambrechtsbos A, Lambrechtsbos B and Tierkloof, was protected up to the stage when each was afforested. In all of the afforested catchments except Biesievlei 20 metre strips were left unplanted along streambanks. The natural vegetation in these strips was left intact and allowed to develop. The rocky cliffs that form part of all the catchments were also left unafforested. In

Tierkloof and Langrivier cliffs comprise large percentages (about 30%) of total area.

Estimation of areal rainfall

Because of the variation in rainfall over the experimental terrain it was necessary to calculate weighted mean catchment rainfall for analysis of runoff: rainfall ratios. Wicht *et al.* (1969) developed a multiple regression model that expressed rainfall at a given point in the study area as a function of altitude and shortest distance from the highest rainfall line, namely the crest of Dwarsberg at the south-eastern end of the valley. Data from twenty raingauges spread through Jonkershoek Valley were used to calculate the model. The parameters of this model were re-evaluated and amended in this study using 15 years of additional rainfall data and the amended model in a metric form is as follows:

$$P = 5\ 713{,}9099 - 1\ 181{,}691\ 500 \log(D) + 0{,}000\ 936\ (H^2)$$

where P = mean rainfall (mm)
D = Distance from the eastern mountain crest (Dwarsberg) (metres)
H = Elevation (metres)

The two independent variables in the recalculated model account for 92% of the variance in rainfall.

When imperial units were used the constants to make this model comparable with the model of Wicht *et al.* (1969) are as follows:

b_1 = 1 169,991 600
b_2 = 0,000 084

The acceptability of the model for calculating the weighted mean catchment rainfall was tested by calculating the residuals as the difference between the measured and model estimated rainfall. All the residuals were plotted against the independant variables of the model developed by Wicht *et al.* (1969) and the model formulated in this study. These results were evaluated by the method of "direct examination of residuals" (Nie *et al.*, 1975). The error components of the regression with the variables, log of distance to Dwarsberg and elevation squared, were found to satisfy the assumptions for regressions. This regression model was thus used to estimate rainfall on grid points representing small areas (about 10 ha) of the catchments. Mean catchment precipitation was weighted by the grid areas.

Streamflow measurement

Streamflow was continuously recorded with water level recorder in a stilling pond at weirs with a 90 degree compound v-notch. Streamflow charts were digitized and streamflow volumes computed. Catchment streamflow was converted to rainfall equivalents in millimetres. The hydrological year (1 April – 31 March) was used in calculating total annual streamflow and rainfall.

Detection and determination of effects of treatment

A calibration method was applied to detect the streamflow changes after afforestation. The dependent variable, streamflow, and independent variable, rainfall, were calibrated against each other by means of linear regression. This was done for a period before treatment, and was used to establish a datum line against which the influence of afforestation on streamflow could be quantified. Streamflow was predicted from the regressions and the difference between predicted and continuously measured streamflow was then accepted as the change due to treatment (Brakensiek and Amerman, 1960; Wicht, 1967b; Van Wyk, 1977 and Van Lill *et al.*, 1980). The calibration method could only be applied in the case of Biesievlei and Tierkloof because these catchments were monitored for 18 and 10 years, respectively, before afforestation. Despite the multiple catchment design, in order to analyse the data, they should be treated as for a paired-catchment design (Hewlett and Pienaar, 1973). The values used to calculate the changes in streamflow are presented in Table 2. These are the mean rainfall ($\bar{P}$) mean streamflow ($\bar{Q}c$) the slope and origin of the regression and features of the regression.

As there was no calibration period before treatment of the remaining catchments it was necessary to look for an alternative method of quantifying changes in streamflow. The method ultimately applied was that of Brakensiek and Amerman (1960), also known as the adjusted values methods. This method takes account of variation in the independent variables of a regression problem by adjusting the dependant variable to a fixed value of the independant variable (in this case the mean). The method was also applied as a check to the Biesievlei and Tierkloof results. The year to year variation in climate was excluded in this way. The reduction in streamflow was calculated by subtracting the adjusted streamflow from the mean streamflow before treatment

TABLE 2
(a) MEAN ANNUAL STREAMFLOW AND RAINFALL FOR DIFFERENT CATCHMENTS, AND (b) VALUES OF REGRESSION EQUATIONS DEPICTING RAINFALL – RUNOFF RELATIONS IN CATCHMENTS FOR THE PERIOD 1940 to 1980

	Bosboukloof	Biesievlei	Lambrechtsbos A	Lambrechtsbos B	Tierkloof	Langrivier
(a)						
Mean annual rainfall, = $\bar{P}$ (mm)	1 296,0	1 427,4	1 413,9	1 472,6	1 809,7	2 261,1
Mean annual streamflow = $\bar{Q}$ (mm)	593,4	663,2	639,5	531,3	1 128,4	1 603,2
(b)						
b_0	– 402,233	– 373,428	– 266,141	– 324,673	– 694,214	– 613,845
b_1	0,643	0,566	0,569	0,517	0,896	0,938
Standard error of regression (mm)	108,7	157,0	108,5	101,1	151,2	155,2
Correlation coefficient	0,83	0,7	0,82	0,83	0,90	0,93

took place. The formula for calculation of the adjusted streamflow values is as follows:

$$Q_{Adj} = Q_t - b_1 [(P - \bar{P}) \text{ or } (Q_c - \bar{Q}_c)]$$

Q_{Adj} = Adjusted streamflow
Q_t = Annual streamflow of treated catchment
b_1 = Slope of regression
P = Annual weighted catchment rainfall
$\bar{P}$ = Annual mean weighted catchment rainfall
Q_c = Annual streamflow of control catchment
$\bar{Q}_c$ = Mean annual catchment streamflow of control catchment

Statistical tests performed showed that the variables in the streamflow series were dependent and abnormally distributed (Fisher, 1954, Shapiro and Wilk, 1965 and Merril and Fox, 1970). Non-parametric methods were therefore used to test statistical significance of streamflow changes. The Wilcoxon-Mann-Whitney test (ZAR, 1974) was applied to streamflow reductions.

Results

Change in streamflow after afforestation

The hypothesis (H_0) that afforestation has no influence on streamflow was tested against the alternative hypothesis (H_1) that afforestation reduces streamflow. The results of the non-parametric Wilcoxon-Mann-Whitney test applied to pre- and post-afforestation reductions in streamflow are presented in Table 3. The value of U leads one to reject the H_0 hypothesis because it is above the test critical values (ZAR, 1974). All of the catchments showed a highly significant reduction in streamflow after afforestation (Table 3). The alternative hypothesis (H_1) that streamflow is reduced by afforestation is therefore accepted.

Changes in streamflow due to afforestation of Bosboukloof (57% afforested), Biesievlei (98% afforested), Tierkloof (36% afforested), Lambrechtsbos B (82% afforested) and Lambrechtsbos A (89% afforested), are reflected in Figures 3, 4, 5, 6 and 7 respectively. Substantial decreases in streamflow were first evident several years after afforestation; seven years in Bosboukloof, four years in Lambrechtsbos B, and three years in Biesievlei, Tierkloof and Lambrechtsbos A. Nänni (1970) stated that the differences in percentage afforestation explain the differences in the magnitude of reductions except in the case of Tierkloof where periods of unusually wet high rainfall may have played a role.

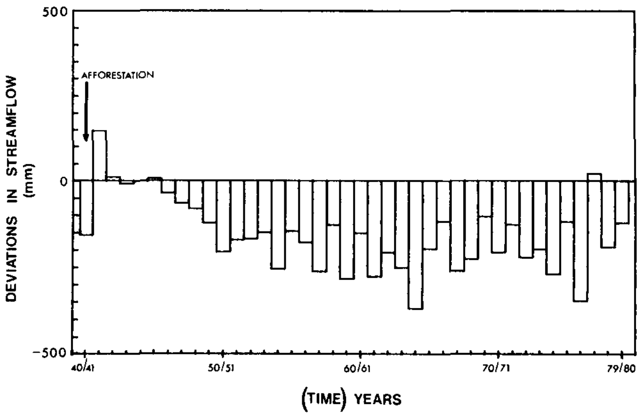

Figure 3
Annual changes in streamflow after 57% afforestation with pines in the Bosboukloof catchments.

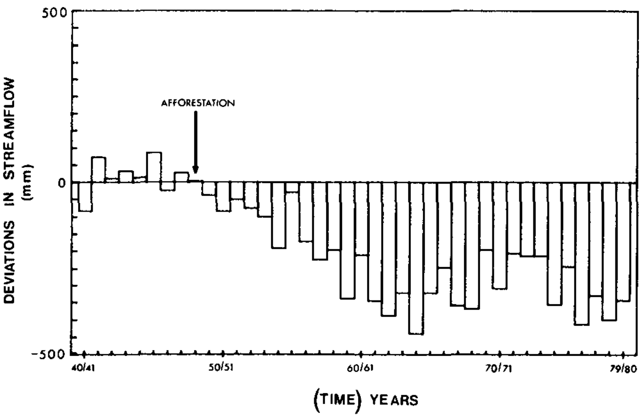

Figure 4
Annual changes in streamflow after 98% afforestation with pines in the Biesievlei catchment.

TABLE 3
RESULTS OF THE ONE TAILED WILCOXON-MANN-WHITNEY TEST COMPARING STREAMFLOW REDUCTIONS BEFORE AND AFTER AFFORESTATION WITH PINES

Catchment	Wilcoxon-Mann-Whitney statistics u	Number of Observations n_1	n_2	Critical values for u 5%	1%	Significance
Bosboukloof	213	7	33	163	181	**
Biesievlei	346	13	27	234	256	**
Tierkloof	335	20	20	262	286	**
Lambrechtsbos B	203	24	9	150	166	**
Lambrechtsbos A	138	27	6	117	131	**

** – Highly significant (1%)
n_1 – Number of observations before treatment
n_2 – Number of observations after treatment

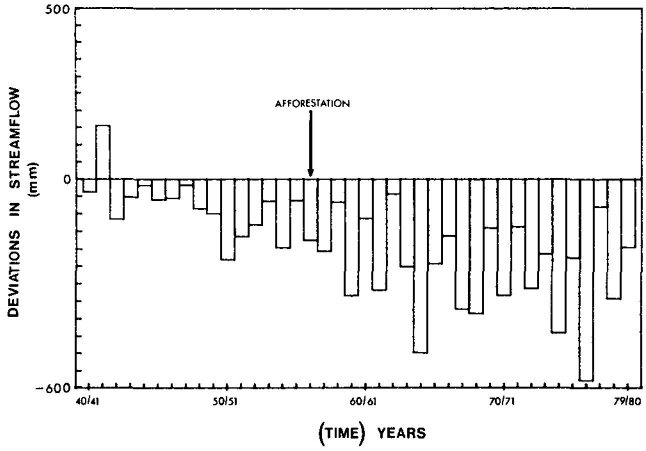

Figure 5
Annual changes in streamflow after 37% afforestation with pines in the Tierkloof catchment.

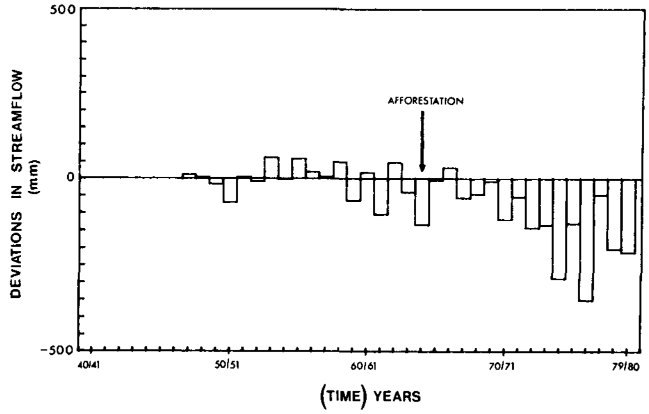

Figure 6
Annual changes in streamflow after 82% afforestation with pines in the Lambrechtsbos B catchment.

The reductions peaked at 19 years in Bosboukloof and 14 years in Biesievlei. After this, water yield levelled off, rising and falling with variation in annual rainfall. For the catchments, Tierkloof, Lambrechtsbos A and Lambrechtsbos B were afforested too recently to enable one to decide whether the reduction in streamflow has peaked. A maximum reduction in streamflow of 442 mm/a was observed at Biesievlei in the 1964/65 season. In the same year a maximum reduction of 369 mm/a was observed at Bosboukloof and 501 mm at Tierkloof. In Table 4 the percentage reductions of the initial flow with their standard errors are presented. The mean decrease in streamflow between 16 and 40 years after afforestation in Bosboukloof was 197 mm/a (from 593 mm) or 33% of initial streamflow. Mean reduction in Biesievlei between 16 and 32 years after afforestation was 313 mm/a (from 663 mm) or 47% of initial streamflow. Streamflow reductions from Tierkloof (36% afforested) stabilized 16 years after afforestation at 171 mm/a and a reduction of 185 mm/a (from 532 mm) was observed 16 years after afforestation in Lambrechtsbos B. In the case of Lambrechtsbos A a mean reduction of 168 mm has been observed after 8 years.

In order to eliminate extreme variability in the annual changes and to synchronize with the layout of the catchment experiment, four-yearly means of the changes in streamflow from afforested catchments were calculated and are presented in Table 5.

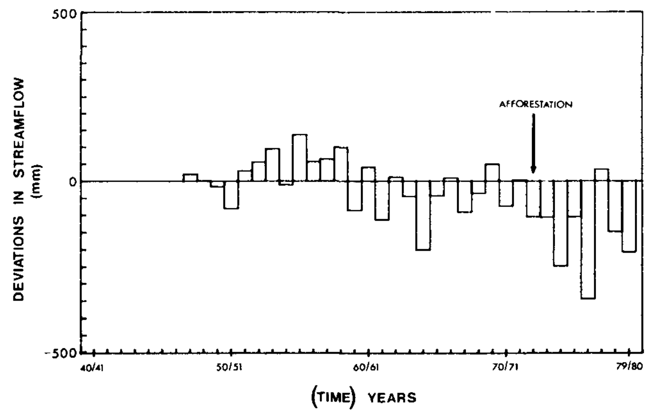

Figure 7
Annual changes in streamflow after 89% afforestation with pines in the Lambrechtsbos A catchment.

Discussion

Due to afforestation the streamflow was significantly reduced within 8 years of planting. The reduction in streamflow of 313 mm/a with a standard error of 22 mm (Table 2) in the case of Biesievlei (98% afforested with a plantation age 32 years) is com-

TABLE 4
CALCULATED STREAMFLOW REDUCTION FROM THE INITIAL FLOW (%) AND THE STANDARD ERROR OF THE STREAMFLOW REDUCTIONS (mm)

	Bosboukloof	Biesievlei	Lambrechtsbos A	Lambrechtsbos B	Tierkloof	Langrivier
Standard error of annual reduction in streamflow (mm)	12,6	21,6	—	41,1	23,8 (7,5 Fynbos)*	9,4
Annual reduction as % of initial flow	33	47	—	34	15 (12 Fynbos)*	12

*Before afforestation

TABLE 5
REDUCTION IN ANNUAL STREAMFLOW (mm), FROM THE JONKERSHOEK CATCHMENTS, OVER SUCCESSIVE FOUR YEAR MEAN VEGETATION AGES FOLLOWING AFFORESTATION WITH *PINUS RADIATA*

	Years after initiation of treatment									
	0–3	4–7	8–11	12–15	16–19	20–23	24–27	28–31	32–35	36–39
Afforestation with *Pinus radiata*										
Bosboukloof	3	25	146	180	213	222	236	166	208	160
Biesievlei	43	101	234	318	343	271	258	373		
Tierkloof	67	53	191	121	171	171				
Lambrechtsbos B	22	37	155	185						
Lambrechtsbos A	142	168								

parable with results from studies elsewhere in this country. Van Wyk (1977), found an average reduction of 249 mm/a (reduction of 41% of the initial flow) due to afforestation with *Pinus radiata* at Bosboukloof (57% afforested with age 28 years) and 313 mm/a (reduction of 47% of the initial flow) at Biesievlei (98% afforested with plantation age 20 years). Wicht (1967) found a reduction of 180 mm at Bosboukloof and 170 mm at Biesievlei over the first 16 years after afforestation. Bosch (1979) found an average reduction of 257 mm/a (reduction of 39% of the initial flow) due to afforestation with *Pinus patula* (74% afforested with plantation age 26 years) at Cathedral Peak, Natal. Van Lill *et al.* (1980) found a reduction of 340 mm/a (reduction of 99% of the initial flow) after afforestation with *Eucalyptus grandis* (100% afforested with a plantation age of 8 years) at Mokobulaan, in the Eastern Transvaal. From these results a clear view of the effect of afforestation in the Republic of South Africa on water supplies can be drawn.

The annual reductions in streamflow after afforestation, as calculated, are variable, with some attaining over 500 mm/a (See Figures 3 to 7). This may be due to variations in climatic factors of which annual rainfall and distribution are expected to be dominant. The annual rainfall and its temporal distribution determine water availability and, consequently, the evapotranspiration rate of the vegetation.

The time series of annual rainfall and streamflow totals presented in Figure 2, shows periodic cycles of high rainfall i.e. from 1953 to 1957, 1960 to 1963 and 1974 to 1977. Reductions in streamflow were highest during high rainfall years. An attempt was made to explain the variability in annual evapotranspiration losses from the catchment by regressing annual reduction in streamflow over annual rainfall and number of raindays. The number of raindays reflects rainfall distribution and therefore soil moisture availability throughout the year. However, the various regression models tested could not explain the variability in annual reduction in streamflow.

Afforested catchments currently occupy only 7% of mountain catchment areas in the Western Cape. Afforestation will therefore not markedly affect total water supply, despite significant decreases in streamflow where trees are planted.

Acknowledgements

I would like to pay tribute to Prof. C.L. Wicht who initiated this study. It is part of the conservation forestry research programme of the Department of Environment Affairs and is published with permission. My thanks are due to Messrs. F.J. Kruger, D.P. Bands, J.M. Bosch and Dr. B.W. van Wilgen for their useful comments, the Jonkershoek technical section for collecting the data Miss R Dreyer for the drawings and Mrs C. Eygelaar for typing.

References

BOSCH, J.M. (1979) Treatment effects on annual and dry period streamflow at Cathedral Peak. *S. Afr. For. J.* **108** 29-38.
BRAKENSIEK, D.L. and AMERMAN, C.R. (1960) Evaluating effect of land-use streamflow. *Agr. Engineering* **41** 158-161.
CAMPBELL, B.M., COWLING, R.M., BOND, W., KRUGER, F.J. (1981) Structural characterization of vegetation in the fynbos biome. South African National Scientific Programmes Report No. 50.
FISHER, R.A. (1954) *Statistical methods for research workers.* 12th edition. Oliver and Boyd Ltd., Edinburgh.
HEWLETT, J.D., PIENAAR, L. (1973) Design and analysis of the catchment experiment. University of Georgia, Athens, USA.
MacVICAR, C.M., DE VILLIERS, J.M. (1977) Grondklassifikasie: 'n Bionomiese Sisteem vir Suid-Afrika. Dept. of Agricultural Technical Services.
MERRIL, W.C. and FOX, K.A. (1970) *Introduction to economic statistics.* John Wiley and Sons., Inc. New York.
NÄNNI, U.W. (1970) The effect of afforestation on streamflow at Cathedral Peak. Report No. 1. *S. Afr. For. J.* **74** 6-12.
NIE, N.H., HULL, C.H., JENKINS, J.G., STEINBRENNER, K. and BENT, D.H. (1975) *Statistical package for the social sciences.* McGraw-Hill Book Company.
SHAPIRO, S.S. and WILK, M.B. (1965) An analysis of variance test for normality. *Biometrika* **42** (3 and 4) 571.
VAN DER ZEL, D.W. and KRUGER, F.J. (1975) Results of the multiple catchment experiments at the Jonkershoek Forestry Research Station, South Africa 2. Influence of protection of fynbos on stream discharge in Langrivier. *For. in S. Afr.* **16** 13-18.
VAN LAAR, A. (1967) The influence of environmental factors on radial growth of *Pinus radiata. For. in S. Afr.* **61**.
VAN LILL, W.S. (1967) Klimaatbeskrywing van die Jonkershoek Bosbounavorsingstasie met die doel om klimaatveranderinge wat stroomafvoer kan beïnvloed, op te spoor. M.Sc. dissertation. University of Stellenbosch.
VAN LILL, W.S., KRUGER, F.J. and VAN WYK, D.B. (1980) The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlect, et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *J. Hydrol.* **48** 107-118.
VAN WILGEN, B.W. (1982) Some effects of post-fire age on above ground plant biomass of fynbos (macchia) vegetation in South Africa. *J. Ecology* **70** 217-225.
VAN WYK, D.B. (1977) Die invloed van bebossing met *Pinus radiata* op die totale jaarlikse afvoer van die Jonkershoek strome. M.Sc. Thesis, Univ. Stellenbosch, (unpublished).
VERSFELD, D.B. (1981) Overland flow on small plots at the Jonkershoek Forestry Research Station. *S. Afr. For. J.* 119.
WICHT, C.L. (1967a) Forest hydrological research in S. Afr. Republic. In W.E. Sopper and H.W. Lull (Editors) *Proceedings of Intern. Symp. on Forest Hydrology.* Penn. State Univ. Pennsylvania, USA 75-84.
WICHT, C.L. (1967b) The validity of conclusions from South African multiple watershed experiments. In W.E. Sopper and H.W. Lull (Editors) *Proceedings of Intern. Symp. on Forest Hydrology.* Penn. State Univ. Pennsylvania, USA 749-760.
WICHT, C.L., MEYBURGH, J.C. and BOUSTEAD, P.G. (1969) Rainfall at the Jonkershoek Forest Hydrological Research Station. *Annals Univ. Stellenbosch* **44** A (1).
ZAR, J.H. (1974) Biostatistical analysis Prenticehall biological sciences series. Englewood Cliffs, N.J. pp. 109-112.