The effects of afforestation on low flows in various regions of South Africa

RE Smith[1]* and DF Scott[2]
[1]*CSIR Division of Forest Science and Technology, PO Box 395, Pretoria 0001, South Africa*
[2]*CSIR Division of Forest Science and Technology, Private Bag X5011, Stellenbosch 7600, South Africa*

Abstract

It may be expected that afforestation has the greatest relative impact on annual streamflow during the low flow periods prior to the first rains of the next season. A paired catchment approach was used to quantify the effect of afforestation with both pines and eucalypts on the low flows of five catchments in the winter and summer rainfall regions of South Africa. Dummy variable analyses were used to test the significance of afforestation on low flows during each year after treatment. Afforestation was found to have a highly significant effect on low flows in all five catchment experiments, with low flows being reduced by up to a 100% in some cases. The effect of afforestation generally appeared to be more marked for eucalypt plantings than for pines, and was manifest at an earlier stage after afforestation. For some catchments (Mokobulaan A and B) these differences became irrelevant as afforestation with both pines and eucalypts eventually caused the streams to dry up.

Introduction

Increased demands are being made on the limited water resources of South Africa as the population continues to expand (Department of Water Affairs, 1986). The demand for wood products, and consequently the rate of afforestation is also growing. Yet afforestation leads to a reduction in catchment water yield (Bosch and Hewlett, 1982; Van Wyk, 1987) so that there is a conflict between managing catchments for both sustained water and timber yields.

From a legal point of view, streams comprise both normal flow and surplus flow. By definition (the Water Act of 1956, Section 53), normal flow is that occurring with such a degree of dependability that it may be used beneficially for irrigation and other purposes without storage. The balance of the water in the stream is referred to as surplus water (Department of Water Affairs, 1986, p. 8.11). During the dry months of the year prior to the first rains of a wet season, normal flow is usually the only water remaining in the streams and it is referred to by hydrologists as low flow.

It is precisely at this low flow time of the year when in-stream water may be needed most critically. Consequently the impact of afforestation on these flows is of particular interest: the effect on low flows may be more important than the overall impacts on streamflow.

It has been clearly demonstrated that changes in vegetal cover may have marked effects on catchment hydrology and that these effects may manifest themselves at different times after treatment (O'Shaughnessy and Moran, 1983). Previous studies have established that afforestation causes reductions in low flows, or conversely that clearfelling of forests causes an increase in low flows. Mid-summer low flows in Jonkershoek in the winter rainfall region of South Africa were reduced by around 52% by complete afforestation with *Pinus radiata* (Banks and Kromhout, 1963). At Cathedral Peak, in the summer rainfall region, afforestation with *Pinus patula* caused reduced low flows, commencing some six to eight years after planting, and levelling off at around a 50% reduction (Bosch 1979). Silvicultural practices did not have a notable effect on streamflow.

In the HJ Andrews Experimental Forest in Oregon, clearfelling and 60% partial felling of Douglas fir forest resulted in a greatly shortened low flow period for at least five years following felling (Harr et al., 1982). In Northern California, selective felling of coniferous forest led to detectable increases in low flow for the next nine years (Keppeler and Ziemer, 1990).

The Coweeta experiments in the southern Appalachian mountains showed that clearfelling forest doubled low flows in the late growing season when streamflow and soil water storage were lowest, but that it had little effect on flows in late winter and early spring when soil water was fully recharged (Swank et al., 1988). In the North-western USA the greatest part of the annual increases in streamflow following felling have been in the fall-winter rainy season, though the largest relative increases were in the summer (low flow) season (Rothacher 1970; 1971; Harr et al., 1979, cited by Harr et al., 1982).

This study quantifies the effect of afforestation, over time, on the low flow of several South African catchments in both summer and winter rainfall regions. This is the first detailed handling of low flows recorded in these catchment experiments. The hypotheses tested are:

- that afforestation causes a significant reduction in seasonal low flows; and
- that the effect is manifest much sooner in catchments afforested with eucalypt species than with pines.

Methods

The paired catchment approach

Four study sites were selected, one in the winter and three in the summer rainfall regions, as afforestation is concentrated in the summer rainfall regions of South Africa. Two of the summer rainfall sites, the Westfalia estate near Tzaneen (23°43'S, 30°04'E) and Mokobulaan situated southeast of Lydenburg (25°17'S; 30°34'E) are in the Eastern Transvaal, while the third, Cathedral Peak (29°00'S; 29°15'E), is situated near Winterton in the Natal Drakensberg (Fig. 1). The winter rainfall site is in the Jonkershoek Valley (33°57'S; 18°15'E), near Stellenbosch in the Western Cape (Fig. 1).

---

*To whom all correspondence should be addressed

Received 8 October 1991; accepted in revised form 27 April 1992.

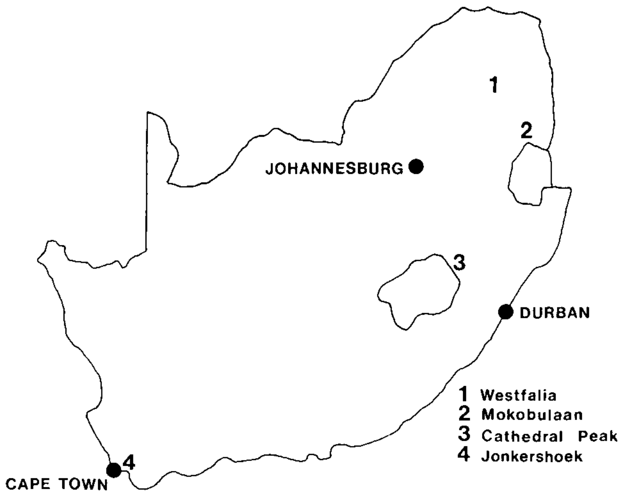

Figure 1
Location of the study sites

The paired catchment experiment approach was used in this study, which is considered by several hydrologists to be the best method for analysing the effect of land-use treatment on streamflow because it compensates for the effects of external influences of differences in vegetation and climate (Hewlett and Pienaar, 1973). Paired catchment experiments are 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. For the analysis, it is further assumed that the difference in soil water storage and water-tightness between the two catchments remains constant (Hewlett, 1982).

In this technique, two catchments (a control catchment and a treated one) are compared over two or more periods of observation (a calibration period and treatment periods). The period prior to the treatment of the vegetation (afforestation in this case) in the treated catchment is referred to as the calibration period. During the calibration period, monthly streamflow totals from the catchment to be afforested are regressed against those of the control catchment. After afforestation, any effect is illustrated by the deviations in streamflow between the expected flow based on the calibration relationship estimates and the real or observed flow measurements.

The afforestation and silvicultural practices used in each of the treatment catchments were the prevailing prescriptions of the then Department of Forestry, which were intended for the production of high volumes of good quality saw-timber. The thinning of trees which took place, though apparently drastic, removed the poorest trees and was aimed at minimum interruption of volume production in the stands. For this reason and as earlier work by Bosch (1979) had shown no response by streamflow at Cathedral Peak to silvicultural practices in the pine plantation, it is not expected that management measures were detectable in the streamflow. Consequently, no effort was made to test for the effects of silvicultural practices in this analysis.

Analyses

Several regression models were tested to find the best relationship between the treated and control catchment low flows during the calibration periods. Different catchment pairs required different models. The selected models were then used to predict low flows, should the catchments not have been afforested. Deviations of the observed low flow values from the predicted model values were then determined to quantify the effect of afforestation on low flows. The increase or decrease in low flow from the treated catchments for each hydrological year after treatment is expressed as a percentage of the predicted low flow had the catchment not been afforested. The hydrological year was defined as the period between October of one year and September of the following year for the summer rainfall region, and between April of one year and March of the following year for the winter rainfall region.

Treatment effects were tested by dummy variable regression analysis (Gujarati, 1978). Dummy variables were assigned values of 0 and 1 for the calibration and treatment periods, respectively, to test the significance of the changes due to afforestation during each hydrological year after treatment. A regression analysis including treatment as a dummy variable (full model) was compared to a model without treatment (reduced model) and an F-test was used to test the significance of the increased sum of squares resulting from the inclusion of the treatment variable.

Defining low flows

Although the concept of low flow appears obvious enough its definition is of necessity arbitrary. Bosch (1979) took low flow as the flow volume in the 50-d period of lowest flow in a year. Harr et al. (1982) used the number of days on which flow was below an arbitrarily fixed level of 0,2 mm/d, while Keppeler and Ziemer (1990) used the number of days that a precipitation index was below 100 mm in the control catchment (approximating a discharge of roughly 0,5 mm/d).

In this study the approach used by Bosch and Smith (1989) was adopted, whereby an arbitrary cut-off value of low flow for each control catchment was selected for the entire study period by observation. The low flow cut-off value was chosen so as to include the flow from the two to three driest months of each year. Months with streamflow lower than this value in the control catchments were selected for analysis and matched with corresponding monthly values in the treated catchments. The selected cut-off value for monthly low flow in each paired catchment study was as follows: 36 mm (Westfalia B and D); 7,5 mm (Mokobulaan catchments A, B and C); 17 mm (Cathedral Peak catchments III and IV) and 13 mm (Jonkershoek's Lambrechtsbos B and Bosboukloof).

Descriptions of the catchments and treatments

Westfalia Estate

Westfalia is situated in the subtropical summer rainfall region, having a mean annual rainfall of 1 600 mm. Precipitation is strongly seasonal with 84% of it falling between October and March. Mean maximum monthly temperatures vary between 21° and 30°C and mean minimum temperatures range between 2° and 10°C (Weather Bureau, 1986). Granite gneiss is the underlying geology (Dohne, 1984). The soils are red, friable, well-drained and well-aerated; predominantly of the Hutton form and Farningham series (terminology after MacVicar et al., 1977).

Of the four gauged catchments at Westfalia, catchments B (control) and D (treated) were selected for analysis in this paper. The reasons for this selection are given in Smith and Bosch (1989). Both catchments have south-easterly aspects and their areas are 33 ha and 40 ha respectively. The vegetation on both catchments was originally indigenous scrub forest. In February 1981, the riparian forest in catchment D was cleared and in December 1982, the rest (83%) of the catchment was cleared and planted with *Eucalyptus grandis* in March 1983. The number of trees per hectare (stems/ha) at planting was 1 370. The first thinning was applied after three years and the stand was reduced to 700 stems/ha. At five years, the stand was further reduced to 450 stems/ha and the final thinning was applied in 1991 leaving 300 stems/ha. The calibration period for this analysis was April 1975 to February 1981. Full details on the experimental layout, site and treatments applied are given in Smith and Bosch (1989), and the preliminary effects of afforestation observed after 3,5 years are given in Bosch and Smith (1989).

Mokobulaan

Mokobulaan is situated on the Eastern Transvaal escarpment. Mean annual precipitation is approximately 1 150 mm and is also strongly seasonal, falling predominantly between October and March. Mean maximum monthly temperatures range between 23° and 29°C and mean minimum temperatures range between 6° and 18°C (Weather Bureau, 1986). The underlying geology comprises basal shales of the Daspoort Stage in the Pretoria series (Van Lill et al., 1980). Although the soils are extremely shallow, being only a few centimetres deep, the underlying rocks are fractured allowing penetration of both roots and water (Van Lill et al., 1980).

Data from all three catchments A, B (both treated) and C (control) were analysed in this paper. All three catchments have an easterly aspect and the original vegetation was a seasonally dry grassland classified by Acocks (1953) as North-eastern Mountain Sourveld. The catchment areas are 26,2, 34,6 and 36,9 ha respectively. Catchment A was planted to *E. grandis* in 1969 (1370 stems/ha at intervals of 2,7 m) and catchment B was planted to *Pinus patula* in January 1971 (same espacement). Catchment C was used as a control for both catchments A and B. Catchment A was thinned in 1974 to 750 stems/ha; in 1979 to 418 stems/ha and in 1983 to 250 stems/ha. The calibration period for catchments A and C was from September 1962 until February 1969 and for B and C from September 1962 until January 1971. The experimental design is described by Nänni (1971) and initial results of the effect of afforestation on annual water yield are given in Van Lill et al. (1980).

Cathedral Peak

Cathedral Peak is located on the middle elevation slopes of the Natal Drakensberg. Mean annual precipitation is 1 550 mm and occurs mainly in summer (October to March). Mean maximum monthly temperatures range between 18° and 26°C and the mean minimum monthly temperatures range between 3° and 14°C (Weather Bureau, 1986). The catchments are underlain by basaltic layers overlying Clarens Sandstone (Bosch, 1979). Soils comprise dark brown loams in the top horizon underlain by clay loams and weathered rock material in the lower horizons. Below this (< 80 cm) is partly decomposed parent rock material which is still suitable for root penetration (Nänni, 1956).

Of the 15 gauged catchments in Cathedral Peak, only catchments III (142 ha) and IV (99 ha) were analysed in this

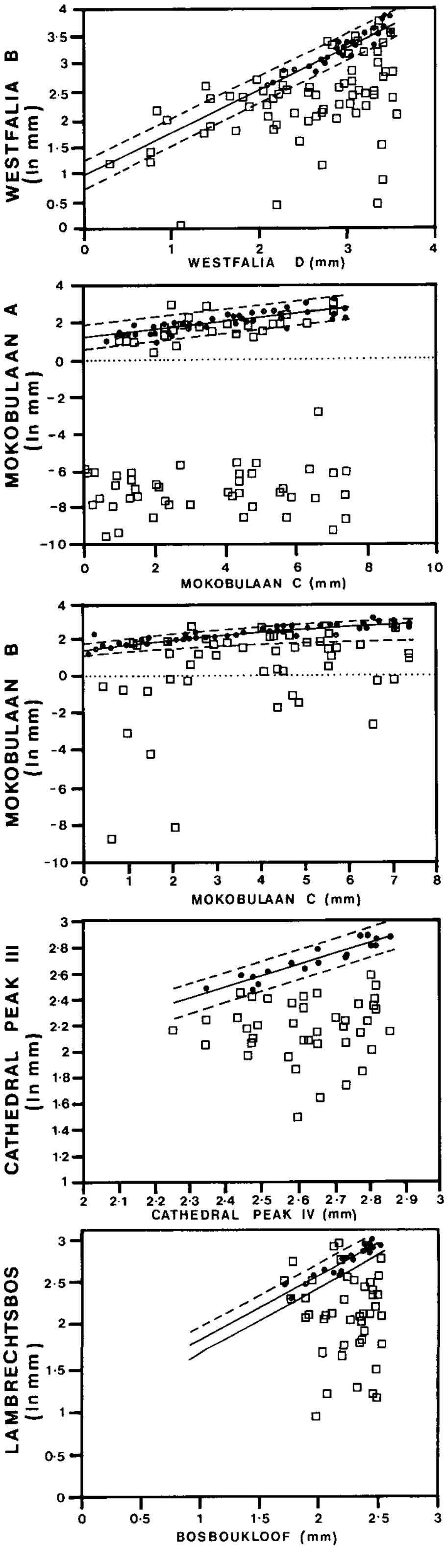

Figure 2
The relationship between monthly low flows (mm) from the treated catchment and the control catchment, where the solid *line represents the regression line for the calibration period and the dotted lines represent the 95% confidence limits. The asterisk represents the pretreatment flows and the squares those after afforestation (Fig. 2a - Westfalia D/B; 2b Mokobulaan A/C; 2c - Mokobulaan B/C; 2d - Cathedral Peak III/IV and 2e - Lambrechtsbos B/Bosboukloof at Jonkershoek).*

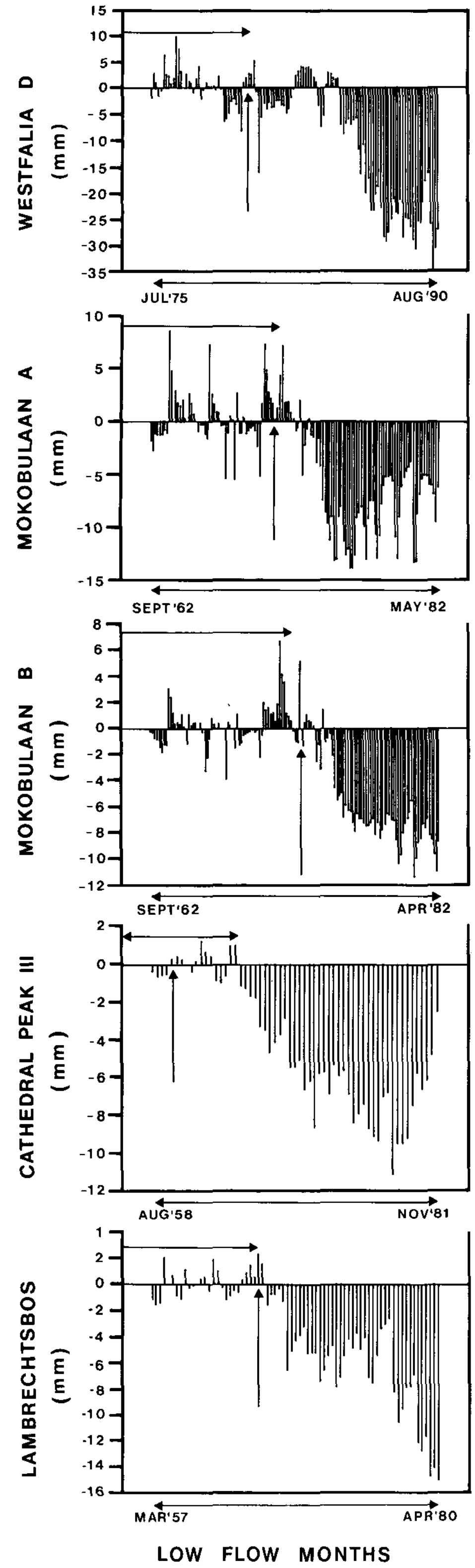

Figure 3

The deviations (vertical bars) in monthly low flow (ln mm) in the treated catchments from values predicted by the calibration period models (Table 1). The calibration period is denoted by the horizontal arrows and the start of afforestation by the vertical arrows (Fig. 3a - Westfalia D/B; 3b -Mokobulaan A/C; 3c - Mokobulaan B/C; 3d - Cathedral Peak III/IV and 3e - Lambrechtsbos B/Bosboukloof at Jonkershoek).

study. The original vegetation in the catchments was a grassland classified by Acocks (1953) as *Themeda triandra* Highland Sourveld. Eighty three per cent of catchment III was afforested with *Pinus patula* during 1958/59. In 1964, 41 ha were destroyed by fire and replanted. In 1969/70, 25% of the plantation in catchment III was thinned by 40% and in 1972, 80% of the plantation was thinned by 40%. In 1981, the entire catchment burnt. Catchment IV is maintained as a grassland through biennial burning (August/September) and served as the control. Accidental fires occurred in this catchment in 1955/56 and 1963/64. Bosch (1979) found that the pines in catchment III only started making discernible demands on catchment water during the eighth year after planting and therefore the calibration period was defined as the period between July 1958 and August 1965. Further details on the experimental layout and initial results are given in Bosch (1979).

Jonkershoek

Mean annual rainfall for the Jonkershoek study sites is 1 440 mm. The rainfall is strongly seasonal with 85% of it falling between April and September. Mean maximum monthly temperature ranges between 17° and 28°C and mean minimum monthly temperatures range between 6° and 14°C (Weather Bureau, 1986). The geology comprises Table Mountain sandstone underlain by Cape granite. A shale band runs through the sandstone and sandstone colluvium material is found throughout the soil profile (Van Wyk, 1987). The major soil forms are Hutton, Magwa and Nomanci (MacVicar et al., 1977).

Of the eight catchments in Jonkershoek, Lambrechtsbos B (treated) and Bosboukloof (control) were selected for this analysis. The natural vegetation in these catchments was tall, open to closed fynbos shrubland. The control catchment of 200,9 ha was 57% afforested with *Pinus radiata* in 1940. Water use reductions due to afforestation peaked at 19 years (silvicultural activities complete) whereafter water yield levelled off, varying only in accordance with annual rainfall (Van Wyk, 1987). The calibration period was therefore selected as the period between February 1960 and February 1965. Lambrechtsbos B (65,5 ha) was 82% afforested in 1964/65 at 1 370 stems/ha (2,7 m espacement). In 1973, the stand was thinned to 770 stems/ha; in 1978 to 510 stems/ha and in 1983 it received a final thinning to 324 stems/ha. According to Van Wyk (1987), substantial reductions in streamflow from Lambrechtsbos B were only evident four years after afforestation.

Results

At all four sites, large reductions in monthly low flow resulted from afforestation. In all five paired catchment studies, the low flows in the post-treatment period fall predominantly below the 95% confidence limits of the calibration period models, indicating the marked effect of afforestation (Fig. 2). These effects are further illustrated (Fig. 3) by the negative deviations about the regression apparent after afforestation. Log-linearised regression models (models, parameters and statistics in Table 1) best described the relationship between the control and treated catchments during the calibration period for all the sites. The calculated decrease in observed low flow relative to predicted flow for each hydrological year after treatment is given (in mm and as a percentage of the predicted flow) in Tables 2 to 6 along with the reduction relative to the 95% confidence limits. Years are given as years after treatment rather than actual dates facilitate comparisons between catchments.

TABLE 1
MODELS, PARAMETERS AND STATISTICS OF THE CALIBRATION REGRESSION EQUATIONS USED IN THE FIVE LOW FLOW ANALYSES (P>F = 0,0001 FOR ALL CATCHMENTS)

Catchments	Regression model	Intercept ln (a)	b	c	F	R^2
Westfalia B vs D	$\ln Y = \ln (a) + b (\ln X)$	0,985	0,763		281,1	0,889
Mokobulaan A vs C	$\ln Y = \ln (a) + b X$	1,143	0,201		84,8	0,616
Mokobulaan B vs C	$\ln Y = \ln (a) + b X + c X^2$	1,471	0,264	-0,014	153,5	0,827
Cathedral Peak III vs IV	$\ln Y = \ln (a) + b (\ln X)$	0,466	0,851		116,0	0,879
Lambrechtsbos vs Bosboukloof	$\ln Y = \ln (a) + b (\ln X)$	1,070	0,748		182,9	0,884

Y = predicted monthly low flow in the treated catchment
X = monthly low flow in the control catchment

TABLE 2
REDUCTIONS IN MONTHLY LOW FLOWS (mm) IN WESTFALIA CATCHMENT D RELATIVE TO THE PREDICTED LOW FLOWS FROM THE MODEL (1), OUTSIDE THE 95% CONFIDENCE LIMITS (2), AS A PERCENTAGE OF THE PREDICTED LOW FLOW IN CATCHMENT D (3), AND AS A PERCENTAGE OF THE PREDICTED FLOW OUTSIDE THE 95% CONFIDENCE LIMITS (4) FOR EACH YEAR AFTER TREATMENT. COLUMN (5) GIVES THE LEVEL OF SIGNIFICANCE (1%-*; not significant - 'ns'). NEGATIVE NUMBERS INDICATE INCREASES

Years	Relative to model (1) (mm)	Relative to confidence limits (2) (mm)	Relative to model (3) (%)	Relative to confidence limits (4) (%)	Level of significance (5)
1	-3,8	-9,1	-3,1	-7,4	*
2	-3,5	-0,4	-2,6	-0,3	*
3	46,8	6,9	22,8	3,4	*
4	163,7	108,1	64,7	42,7	*
5	179,1	127,9	76,7	54,8	*
6	99,3	70,3	75,2	53,3	*
7	202,6	146,5	79,2	57,3	*
8	135,2	102,2	90,0	68,1	*

Years are hydrological years after treatment, October - September

Westfalia Estate

In the first two years following the clearing of the indigenous forest and the planting of eucalypts in catchment D of Westfalia, a significant increase in low flow was detected (Table 2). This is also illustrated by the positive deviations in Fig. 3a. From the third year until the end of the study period, low flows declined significantly (Fig. 2a) as illustrated by the increasingly negative deviations in Fig. 3a, with flow in catchment D being 79% (203 mm) and 90 % (135 mm) lower than predicted flow in the seventh and eighth years after afforestation respectively (Table 2). Calculated from outside the 95% confidence limits for the calibration equation, the reduction for these two years was 57% (147 mm) and 68% (102 mm; Table 2). The stream dried up during October (the driest month of the year) of the last two years of the study (1989 to 1990), but started flowing again after the first rains in the wet season.

TABLE 3
REDUCTIONS IN MONTHLY LOW FLOWS (mm) IN MOKOBULAAN CATCHMENT A RELATIVE TO THE PREDICTED LOW FLOWS FROM THE MODEL (1), OUTSIDE THE 95% CONFIDENCE LIMITS (2), AS A PERCENTAGE OF THE PREDICTED LOW FLOW IN CATCHMENT A (3), AND AS A PERCENTAGE OF THE PREDICTED FLOW OUTSIDE THE 95% CONFIDENCE LIMITS (4) FOR EACH YEAR AFTER TREATMENT. COLUMN (5) GIVES THE LEVEL OF SIGNIFICANCE (1% -*; not significant - 'ns')

Years	Relative to model (1) (mm)	Relative to confidence limits (2) (mm)	Relative to model (3) (%)	Relative to confidence limits (4) (%)	Level of significance (5)
1	27,7	0,0	26,5	0,0	ns
2	61,3	0,5	58,0	0,4	ns
3	65,8	3,3	77,0	3,9	*
4	71,2	12,2	90,5	15,5	*
5	.	.	.	.	.
6	74,5	18,4	100,0	24,7	*
7	69,0	16,8	100,0	24,3	*
8	149,5	37,1	100,0	24,8	*
9	105,4	25,3	100,0	24,0	*
10	148,3	37,3	100,0	25,1	*
11	118,8	31,0	100,0	26,1	*
12	122,9	32,5	100,0	26,5	*

Years are hydrological years after treatment, October - September.
. = all flow above cut-off low flow value in that year.

TABLE 4
REDUCTIONS IN MONTHLY LOW FLOWS (mm) IN MOKOBULAAN CATCHMENT B RELATIVE TO THE PREDICTED LOW FLOWS FROM THE MODEL (1), OUTSIDE THE 95% CONFIDENCE LIMITS (2), AS A PERCENTAGE OF THE PREDICTED LOW FLOW IN CATCHMENT B (3), AND AS A PERCENTAGE OF THE PREDICTED FLOW OUTSIDE THE 95% CONFIDENCE LIMITS (4) FOR EACH YEAR AFTER TREATMENT. COLUMN (5) GIVES THE LEVEL OF SIGNIFICANCE (1% - *; not significant - 'ns'). NEGATIVE NUMBERS INDICATE INCREASES

Years	Relative to model (1) (mm)	Relative to confidence limits (2) (mm)	Relative to model (3) (%)	Relative to confidence limits (4) (%)	Level of significance (5)
1	-0,6	0,0	-1,1	0,0	ns
2	4,0	0,0	8,7	0,0	ns
3	3,4	0,0	8,6	0,0	ns
4	.	.	.	.	.
5	15,4	0,0	40,5	0,0	*
6	17,9	0,02	48,8	0,1	*
7	41,2	2,6	54,2	3,4	*
8	36,6	6,8	62,5	11,6	*
9	66,6	23,9	73,4	26,3	*
10	64,6	29,7	85,3	39,2	*
11	66,1	30,1	86,3	39,4	*

Years are hydrological years after treatment, October - September.
. = all flows above cut-off low flow value in that year.

Mokobulaan

Mokobulaan catchment A showed significant reductions in low flow from the third year after afforestation with eucalypts until the end of the study period (Table 3). These significant reductions in low flows are illustrated by the large negative deviations in flow seen in Fig. 3b. Low flows decreased rapidly after the third post-treatment year reaching a 100% (75 mm) reduction in the sixth year after afforestation, causing the stream to dry up during the low flow period. This highly significant (Table 3) reduction in low flow was consistent over the remainder of the study period (as is evident in Fig. 2b) and resulted in the stream drying up completely, i.e. throughout the year, in April 1977.

In catchment B, low flow remained relatively unaffected by afforestation with pines during the first four years after treatment. From the fifth year, significant reductions in low flow were detected (Figs. 2c and 3c). These reductions in low flow, although highly significant, were slower to develop in the pine stand than was the case in the eucalypt catchments at Westfalia and Mokobulaan A, with flow being 63% (37 mm) lower than predicted in the eighth year after afforestation as compared to 90% and 100% for Westfalia and Mokobulaan A respectively (Table 4). In time, low flows dropped further with reductions being 85% (65 mm) in the tenth and eleventh years after afforestation. Streamflow dried up entirely during May 1982 (12th year after afforestation).

Cathedral Peak

In Cathedral Peak catchment III, a significant decline in low flow was only evident in the eighth year after afforestation and the decline continued steadily over the remainder of the treatment period (Table 5; Fig. 3d). The reductions in low flow due to afforestation with pines at Cathedral Peak were somewhat lower than those due to afforestation at Westfalia and Mokobulaan. Low flows in Cathedral Peak catchment III in the eighth year after afforestation were only 11% (4 mm) lower than predicted as compared to the 90%, 100% and 60% reductions at Westfalia, Mokobulaan A and B respectively. Although streamflow continued to decrease over the next 15 years, these reductions remained lower than those recorded at Westfalia and Mokobulaan A and B, both in absolute terms (mm per year) and as percentages of predicted low flow.

Jonkershoek

Low flows in Lambrechtsbos B showed a steady significant reduction from the fifth year after treatment (Table 6; Figs. 2e and 3e). At seven to eight years after afforestation, low flow was approximately 40% (29 mm) lower than the predicted flow for that catchment. This reduction is similar to that found for Mokobulaan B at this stage after afforestation. Low flow was further reduced over the next eight years to almost 78% of the predicted flow, slightly higher than the reductions measured at Cathedral Peak but slightly lower than at Mokobulaan B at comparable times after planting.

Discussion

In all the above catchment studies, afforestation with both pines and eucalypts caused highly significant reductions in annual low flows, supporting the hypothesis that afforestation causes a significant decline in seasonal low flows. This result was not unexpected, and is in agreement with reductions recorded in other afforestation studies (Banks and Kromhout, 1963; Bosch, 1979). The results are analogous to those of deforestation studies (Harr et al., 1982; Keppeler and Ziemer, 1990) where summer base flows increased after treatment.

In some instances (e.g. Westfalia), slight increases in streamflow were evident in the first year or so after treatment. The most likely explanation for this is that a vegetation type with a comparatively high water use (mature indigenous forest) is being cleared and replaced with seedlings which use comparatively little water initially. This theory is supported by the fact that the same effect is not evident at Cathedral Peak, Mokobulaan or Lambrechtsbos where seedlings were planted into the intact natural vegetation of the catchments. In these cases, seedling water use would have been in addition to that of the grassland or fynbos, rather than instead of it.

None of the catchments in this study showed a significant decline in annual low flows during the first two years after treatment. The effect of afforestation on low flows does appear to manifest itself sooner with eucalypt plantings than with pines. The low flows in both the catchments planted with eucalypts showed a significant response to treatment from the third year after afforestation, whereas the catchments planted with pines only responded to afforestation from the fifth year onwards. At the same time after treatment, the effect of afforestation with eucalypts is far greater than that of pines. Due to some of the catchments drying up during the study period, and hence a lack of data for comparison, it is difficult to make valid comparisons between the long-term effects of pines and eucalypts on low flows. Both eucalypt (Westfalia, Mokobulaan A) and pine (Mokobulaan B) planted catchments did dry up though. Bosch and Hewlett (1982) suggested that decreases in water yield following afforestation are proportional to the growth rate of the cover type. The faster growth rates of the eucalypts in the first eight years after planting may therefore explain their earlier and greater impact on the low flows. As the eucalypts mature beyond this rapid growth phase, the difference between their effects on low flows and that of pine may be expected to diminish. For example, the percentage low flow reduction (86%) at Mokobulaan B (pines) in the eleventh year after treatment is similar to that at Westfalia (eucalypts) at eight years (90%).

The low flow response in the two eucalypt catchments was remarkably similar when compared to the response recorded in the three pine catchments. The greatest reduction in low flows after afforestation with pines was found at Mokobulaan B, where the effect of the pines was similar to that of the eucalypts at Westfalia and Mokobulaan A. This was possibly due to the similar growing conditions in these three catchments and the comparatively rapid growth rate of *Pinus patula* under subtropical conditions. The small and slower effect of *P. patula* at Cathedral Peak is most probably due to the less favourable growing conditions. The soils are poorer and the climate harsher at Cathedral Peak than at Mokobulaan, resulting in slower growth rates. The slower and smaller response of low flows to afforestation with pines at Lambrechtsbos as compared to those at Mokobulaan, may be due to similar differences in growth rate. Soils in fynbos catchments are usually shallow, rocky and nutrient deficient as compared to those in the subtropical Eastern Transvaal regions (Mokobulaan and Westfalia), leading to comparatively poorer tree growth. The growth rate of *P. radiata*

TABLE 5
REDUCTIONS IN MONTHLY LOW FLOWS (mm) IN CATHEDRAL PEAK CATCHMENT III RELATIVE TO THE PREDICTED LOW FLOWS FROM THE MODEL (1), OUTSIDE THE 95% CONFIDENCE LIMITS (2), AS A PERCENTAGE OF THE PREDICTED LOW FLOW IN CATCHMENT III (3), AND AS A PERCENTAGE OF THE PREDICTED FLOW OUTSIDE THE 95% CONFIDENCE LIMITS (4) FOR EACH YEAR AFTER TREATMENT. COLUMN (5) GIVES THE LEVEL OF SIGNIFICANCE (1% - *; not significant - 'ns'). NO SIGNIFICANT DIFFERENCES BETWEEN THE TREATED AND CONTROL CATCHMENTS IN YEARS ONE TO SEVEN (BOSCH, 1979)

Years	Relative to model (1) (mm)	Relative to confidence limits (2) (mm)	Relative to model (3) (%)	Relative to confidence limits (4) (%)	Level of significance (5)
8	4,2	0,58	11,2	1,5	*
9	5,1	2,2	18,0	7,8	*
10	12,3	7,9	28,8	18,5	*
11	12,1	7,8	28,6	18,3	*
12	23,3	17,0	37,7	27,5	*
13	8,7	7,0	52,5	42,3	#
14	5,8	4,3	38,5	28,2	#
15	18,0	13,2	38,8	28,6	*
16	5,9	4,4	40,4	30,2	#
17	21,0	16,2	44,8	34,6	*
18	15,5	12,1	46,8	36,6	*
19	17,9	14,6	54,7	44,6	*
20	23,4	18,4	47,5	37,4	*
21	.	.	.	.	.
22	30,2	25,5	64,7	54,5	*
23	35,4	27,9	48,1	37,9	*

Years are hydrological years after treatment, October - September.
# = biased estimates of parameters because of too few data.
. = all flow above cut-off low flow value in that year.

is also much slower than that of *P. patula* (Loveday, 1983). But this difference between the effects of pines at Jonkershoek and Mokobulaan may also be due to the pretreatment vegetation, fynbos, having a higher inherent water use than the grassland sites, making differences in water yield after afforestation less marked. Initially, both the fynbos and small seedlings are using water. The growth of pine seedlings is slow initially (hence the delayed response of low flows to afforestation) and water use increases gradually as the pine seedlings establish themselves. As the forest canopy develops and overshadows the fynbos scrubland, the fynbos dies back and low flow reduction is solely the result of afforestation.

Based on the finding that the clearing of forest causes greater absolute increases in water yield in high rainfall regions than in low rainfall regions (Bosch and Hewlett, 1982) it may be hypothesised that reductions in low flows following afforestation would be similarly positively related to rainfall. Our results, obtained over a relatively small range of mean annual precipitation (MAP), do not support this hypothesis. The largest absolute reductions in low flow (200 mm) were recorded at Westfalia D which has the highest rainfall (MAP = 1 600 mm), but the second highest absolute reductions (150 mm) were seen at Mokobulaan A which has the lowest MAP of 1 150 mm. In this study the reductions appear to be more likely related to the tree species (eucalypt vs pine) and to tree vigour or growth rate.

A large proportion (between 82 and 100%) of each of the catchments described in this analysis was afforested and it is probable that if smaller sections had been afforested, low flow reductions may have been proportionately smaller. From a review of 94 catchment experiments, Bosch and Hewlett (1982) concluded that mature conifers and eucalypts cause an average change of 40 mm in annual water yield for each 10% of the catchment which changes cover. So it seems reasonable to expect that the reductions in low flow would similarly be related to the extent of afforestation. From the limited sampling of this study it is roughly estimated that eucalypts and pines reduce annual low

TABLE 6
REDUCTIONS IN MONTHLY LOW FLOWS (mm) IN LAMBRECHTSBOS B RELATIVE TO THE PREDICTED LOW FLOWS FROM THE MODEL (1), OUTSIDE THE 95% CONFIDENCE LIMITS (2), AS A PERCENTAGE OF THE PREDICTED LOW FLOW IN LAMBRECHTSBOS B (3), AND AS A PERCENTAGE OF THE PREDICTED FLOW OUTSIDE THE 95% CONFIDENCE LIMITS (4) FOR EACH YEAR AFTER TREATMENT. COLUMN (5) GIVES THE LEVEL OF SIGNIFICANCE (1% - *; not significant - 'ns')

Years	Relative to model (1) (mm)	Relative to confidence limits (2) (mm)	Relative to model (3) (%)	Relative to confidence limits (4) (%)	Level of significance (5)
1	-3,9	0,0	-12,5	0,0	ns
2	3,1	0,0	6,8	0,0	ns
3	1,6	0,0	4,5	0,0	ns
4	.	.	.	.	.
5	20,1	12,6	34,4	21,5	*
6	13,7	7,8	29,8	17,0	*
7	29,2	18,9	36,5	23,7	*
8	29,8	20,7	42,3	29,4	*
9	39,8	27,8	43,7	30,6	*
10	31,5	22,7	52,0	39,2	*
11	15,6	10,9	42,2	29,6	*
12	7,29	14,6	38,9	26,2	#
13	.	.	.	.	.
14	24,9	20,3	67,7	55,0	*
15	40,8	34,2	77,8	65,1	*
16	15,0	12,9	77,6	65,0	*

Years are hydrological years after treatment, April - March.
# = biased estimates of parameters because of too few data.
. = all flow above cut-off low flow value in that year.

flow by between 2 and 18 mm and 1,5 to 3 mm, respectively, for each 10% of the catchment that is afforested.

Although the results of this study relate to specific catchments with specific characteristics, they broadly agree with the results from a number of other catchment studies world-wide and therefore can be considered to be representative of generally applicable principles. The implications of these results for land-use managers are quite serious if water yield during the dry season or low flow periods is a critical issue for downstream users, especially in cases where streamflow dries up completely.

In the two instances (Mokobulaan A and B) where catchments were planted right through the riparian zones, streamflow dried up entirely. This could be seen as evidence in support of the theory that plants in riparian zones use water extravagantly (Banks, 1961; Rowe, 1963; Horton, 1972; Bosch and Versfeld, 1983). It may, therefore, be advisable to restrict afforestation in areas of the catchment that are known to be intermittently saturated (e.g. riparian zones, marshes, springs) where use of water by vegetation is possibly higher simply due to its greater availability. More specific work needs to be done on this aspect.

The tree seedlings were planted into shallowly prepared pits without fertilisation. Modern practice is to intensively prepare the site to improve root penetration and apply fertiliser to boost early growth. Such establishment practices are likely to cause earlier reductions of low flows from the afforested catchments because the site is fully exploited by the trees sooner.

Conclusions

Afforestation does reduce low flow yields significantly during the dry periods of the year prior to the wet season and this will have implications for downstream water users. The effect appears to be more marked for eucalypts (90 to 100% reductions) than pines (40 to 60% reductions) in the first eight or so years after treatment, but differences may diminish as the pine stands become well-established. This supports the hypothesis that pine plantations manifest the effects of afforestation on low flow at a later stage after afforestation than eucalypts. The final impact of afforestation on low flows may eventually be the same for a particular region irrespective of species, in that in the one directly comparable situation (Mokobulaan A and B) the streams in both the pine and eucalypt catchments dried up completely. The impacts of afforestation on low flows are expected to be less if smaller proportions of the catchment are planted up, and especially if the unplanted areas include the saturated zones.

Acknowledgements

The sterling work of all those involved in data collection and instrument maintenance in each of the catchments countrywide is gratefully acknowledged. Other colleagues to be thanked for assistance with editing earlier drafts of this paper include Arthur Chapman and Danie Van Wyk. This research was funded by the Forestry Branch of the Department of Water Affairs and Forestry, whose support is gratefully acknowledged. Conclusions drawn from the work are not necessarily those of the Department of Water Affairs and Forestry.

References

ACOCKS, JPH (1953) Veld types of South Africa. *Mem. Bot. Surv. S. Afr.* **28** 192.

BANKS, CH (1961) The hydrological effects of riparian and adjoining vegetation. *For. S. Afr.* **1** 31-46.

BANKS, CH and KROMHOUT, C (1963) The effect of afforestation with *Pinus radiata* on summer baseflow and total annual discharge from Jonkershoek catchments. *For. S. Afr.* **3** 43-65.

BOSCH, JM (1979) Treatment effects on annual and dry period streamflow at Cathedral Peak. *S. Afr. For. J.* **108** 29-38

BOSCH, JM and HEWLETT, JD (1982) A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* **55** 3-23.

BOSCH, JM and VERSFELD, DB (1983) Forestry and the management of riparian zones. Internal report of the South African Forestry Research Institute, Jonkershoek Forestry Research Centre, Stellenbosch.

BOSCH, JM and SMITH, RE (1989) The effect of afforestation of indigenous scrub forest with *Eucalyptus* on streamflow from a small catchment in the Transvaal, South Africa. *S. Afr. For. J.* **150** 7-17.

DEPARTMENT OF WATER AFFAIRS (1986) *Management of the Water Resources of the Republic of South Africa.* Department of Water Affairs, Pretoria.

DÖHNE, A (1984) Soil survey (AD7) of the Westfalia conservation catchments. Unpublished report, Department of Environment Affairs, Sabie Forestry Research Centre, Sabie.

GUJARATI, D (1978) *Basic Econometrics.* McGraw-Hill, New York.

HARR, RD, LEVNO, A and MERSEREAU, R (1982) Streamflow changes after logging 130-year-old Douglas Fir in two small watersheds. *Water Resour. Res.* **18** 637-644.

HEWLETT, JD (1982) *Principles of Forest Hydrology.* University of Georgia Press, Athens. 183 pp.

HEWLETT, JD and PIENAAR, L (1973) Design and analysis of the catchment experiment. In: White, EH (ed.) *Proc. Symposium on Use of Small Watersheds in Determining Effects of Forest Land Use on Water Quality.* University of Kentucky, Lexington, KY. 88-106.

HORTON, JS (1972) Management problems in phreatophyte and riparian zones. *J. Soil and Water Cons.* **27** 58-61.

KEPPELER, ET and ZIEMER, RR (1990) Logging effects on streamflow: Water yield and summer low flows at Caspar Creek in Northwestern California. *Water Resour. Res.* **26** 1669-1679.

LOVEDAY, NC (1983) Yield tables for the major timber species. In: Odendaal, PB, Owen, DL, Bosman, DL, Von Gadow, K and Van der Zel, DW (eds.) *South African Forestry Handbook*, South African Institute of Forestry, Pretoria. 134-150.

MACVICAR, CN, DE VILLIERS, JM, LOXTON, RF, VERSTER, E, LAMBRECHTS, JJN, MERRYWEATHER, FR, LE ROUX, J, VAN ROOYEN, TH and VON HARMSE, HJ (1977) *Soil Classification - A Binomial System for South Africa.* Department of Agricultural Technical Services, Pretoria. 150 pp.

NÄNNI, UW (1956) Forest hydrological research at the Cathedral Peak Research Station. *S. Afr. For. J.* **27** 2-35.

NÄNNI, UW (1971) The Mokobulaan research catchments. *S. Afr. For. J.* **78** 5-13.

O'SHAUGHNESSY, PJ and MORAN, RJ (1983) The influence of change from or to afforestation upon catchment hydrology. Paper presented at the 1983 *Water Research Foundation Symposium*, Adelaide.

ROTHACHER, J (1970) Increases in water yield following clearant logging in the Pacific Northwest. *Water Resour. Res.* **6** 653-658.

ROTHACHER, J (1971) Regimes of streamflow and their modification by logging. In: Morris, J (ed.) *Symposium on Forest Land Uses and Stream Environment.* Continuing Education Publications, Oregon State University, Corvallis, Oregon. 40-54.

ROWE, PB (1963) Streamflow increases after removing woodland-riparian vegetation from a southern California watershed. *J. For.* **61** 365-369.

SMITH, RE and BOSCH, JM (1989) A description of the Westfalia catchment experiment to determine the effect on water yield of clearing the riparian zone and converting an indigenous forest to a eucalypt plantation. *S. Afr. For. J.* **151** 26-31.

SWANK, WT, SWIFT, LW and DOUGLASS, JE (1988) Chapter 22: Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In: Swank, WT and Crossley, DA (eds.) *Forest Hydrology and Ecology at Coweeta.* Ecological Studies Volume **66**; Springer, New York.

VAN LILL, WS, KRUGER, FK and VAN WYK, DB (1980) The effects of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *J. Hydrol.* **48** 107-118.

VAN WYK, DB (1987) Some effects of afforestation on streamflow in the western Cape Province, South Africa. *Water SA* **13**(1) 31-36.

WEATHER BUREAU (1986) *Climate of South Africa - Climate Statistics up to 1984 (WB40).* Weather Bureau, Department of Environment Affairs, Government Printer, Pretoria.