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The response in water yield to the thinning of *Pinus radiata*, *Pinus patula* and *Eucalyptus grandis* plantations

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Abstract

The paired catchment method was used to test for the effects of thinning on the water yield in three afforested catchments in South Africa, namely, Biesievlei, Jonkershoek, 98% afforested with *Pinus radiata* (three thinnings); Westfalia catchment D, 100% afforested with *Eucalyptus grandis* (two thinnings); and Cathedral Peak CII that was 74% afforested with *Pinus patula* (one thinning). During and after two separate thinnings, each of which removed roughly one third of the stems in a maturing *P. radiata* plantation in the Biesievlei catchment, annual streamflow increased by between 10 and 71% (19–99 mm). These increases persisted for three and two years after the thinning, respectively. A final thinning in the same catchment removed only 22% of stems at an age of 28 yr. The following years (1977 and 1978) were wetter than average, and reductions in annual streamflow of 26 and 55% were recorded in these two years. At Westfalia catchment D and Cathedral Peak CII, the hydrological trends were entirely dominated by the rapidly declining streamflow caused by the developing *E. grandis* and *P. patula* plantations respectively. Any savings in water use that may have resulted from the thinning of these plantations were insufficient to affect the downward trend in annual streamflow. Thinnings may have had a minor effect of delaying or reducing the desiccation of these catchments but such effects could not be assessed due to natural variability and the limited resolution of the paired catchment method. The trends in total water yield from the catchments were generally mirrored in the dry season streamflow, and there were no strong indications that thinning effects are linked to a particular season. © 1997 Elsevier Science B.V.

Keywords: Eucalypts; Pine; Plantations; Streamflow; Thinning; Water yield

1. Introduction

Thinnings are an essential part of modern plantation silviculture. They involve the marking, felling and removal of a proportion of the trees in the stand. Thinnings are usually applied to redistribute the growth potential of the plantation so that timber yields, quality and economic returns are optimised. Ideally, the poorest trees are selectively removed and competitive suppression of growth in the best trees prevented. Material resulting from the thinnings, especially later in the plantation rotation, can also provide an interim crop in the form of poles or pulpwood.

The removal of trees will change the canopy cover and structure and may increase the water yield from a catchment. An increase in water yield, especially during drought conditions, could be an important factor for down-stream users and a useful tool in

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integrated catchment management. It is thus important to ascertain what effect the removal of up to 45% of a plantation will have on the water yield from the catchment.

The only previous analysis of the effects of thinning of plantations in South Africa on streamflow was by van der Zel (1970). He studied the effect of the second thinning of the *Pinus radiata* plantation in Biesievlei catchment in Jonkershoek, Western Cape, on streamflow in January. He estimated that there was a 50% increase in annual streamflow as a result of a 33% removal of stems at 16 yr age, and that the increase persisted for three years. The increase was ascribed to a reduction in evapotranspiration due to the reduction in canopy cover.

Elsewhere, thinnings have been shown to increase water yield in proportion to the portion of the catchment cleared (Bosch and Hewlett, 1982) or of the canopy removed (Baker, 1986). The persistence of the water yield increases seems to relate of the size of the initial response, the evaporation demand on the site and the growth rate of the trees. A heavy thinning that removed 76% of canopy in a humid jarrah (*Eucalyptus marginata*) forest in Western Australia increased streamflow by 260 mm a^{-1}, from only 6% of annual rainfall to 20% of annual rainfall (Ruprecht et al., 1991). Thinning of ponderosa pine forest in Northern Arizona led to water yield increases that were positively related to the portion of over-storey removed, and persisted for between three to ten years with cooler catchments taking longer to return to pre-thinning levels (Baker, 1986). Strip thinning that removed 50% of a 40 year old *Eucalyptus regnans* forest in Victoria, Australia, stimulated growth in the residual crop but nonetheless led to streamflow increases of between 21–31% (O'Shaughnessy et al., 1993).

It is to be expected that a reduced canopy density will allow more rainfall to reach the forest floor, allowing greater recharge of soil water. This has been shown experimentally in plantings of *Eucalyptus grandis*, where total water use was proportional to stand density and the amount of deep drainage was inversely proportional to stand density (Eastham et al., 1988). The more widely spaced trees in this experiment (304 and 825 spha) were probably not in competition with each other. Experimental work in South Africa has shown that there is a positive response in timber growth rate to thinnings that may lead to a greater eventual stand volume (van Laar, 1979).

The developmental homeostasis argument of Jarvis (1975) and Whitehead et al. (1984) hypothesizes that a forest stand, regardless of stocking, will tend to develop to fully utilize the site. The individual trees remaining after a thinning re-equilibrate by increasing their leaf area (ultimately restoring the previous leaf area index of the stand), expanding their sapwood conducting area (thus, reducing the resistance pathway between soil and leaf) and in-

Table 1
Selected physical features of the catchments used in this study (data from Nänni, 1956; Bosch, 1979; van Wyk, 1987; Smith and Bosch, 1989)

Catchment name	Area (ha)	Percentage afforestation	Elevation (m)	Mean *slope*[a] (%)	M*AP*[b] (mm)	M*AR*[c] (mm)
Western Cape						
Biesievlei	27.2	98	280–300	23	1427	663
Bosboukloof	200.9	57	270–780	26	1296	593
Lambrechtsbos-A	31.2	0 till 1972	366–1067	45	1414	660
Langrivier	245.8	0	366–1460	40	2261	1603
Northern Province						
Westfalia B	32.4	0	1050–1430	42	1597	543
Westfalia D	39.6	83	1050–1320	33	1611	548
KwaZulu-Natal Drakensberg						
Cathedral Peak CII	190.7	74	1845–2454	45	1680	628
Cathedral Peak CIV	94.7	0	1845–2226	35	1420	742

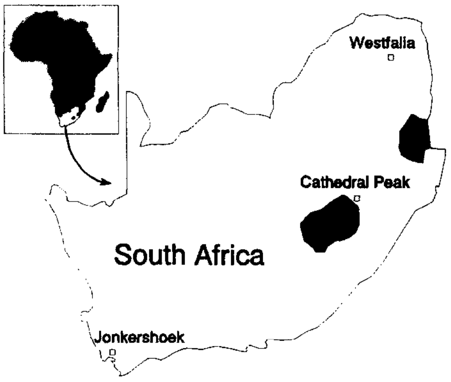

Fig. 1. The general location of the research catchments used in this study.

creasing transpiration flux. A response in water yield from a thinned stand could only be expected, therefore, in the interim period until the equilibrium condition is re-established. In a specific study of *Pinus sylvestris* in Northern Scotland, full equilibrium had not been established 14 yr after the last thinning (Whitehead et al., 1984).

In this study, we report on the effects on streamflow of thinnings in three different climatic regions in South Africa.

2. Experimental areas and methods

2.1. Description of the experimental areas

The thinning of plantations in three experimental catchment areas in South Africa were studied. These areas were: Jonkershoek, 10 km east of Stellenbosch in the Western Cape Province; Westfalia, just north of Tzaneen in the Northern Province; and Cathedral Peak, 42 km south-west of Bergville in the KwaZulu-Natal Drakensberg (Fig. 1).

Jonkershoek has a Mediterranean-type climate, with more than 80% of rainfall during the seven-month period from April to October (Wicht et al., 1969). The underlying bedrock of most of the afforested area is deeply weathered Cape Granite, with a shale lens (Malmesbury Group) on top of the granites, cutting across the catchments. The granite and the overlying sandstone (Table Mountain Group, Cape Supergroup), give rise to the coarse colluvial soils, that have high infiltrability (Versfeld, 1981). The predominant soils are freely drained, yellow and red loams to sandy-loams. The natural vegetation of the area is fynbos, with Protea species prominent, and evergreen forests in protected sites, such as along rivers and on scree slopes (van Wilgen, 1982). Additional features are summarised in Table 1 and van Wyk (1987).

In contrast to Jonkershoek, Westfalia lies in the sub-tropical summer rainfall area, with 84% of the rain falling from October to March (Table 1). The

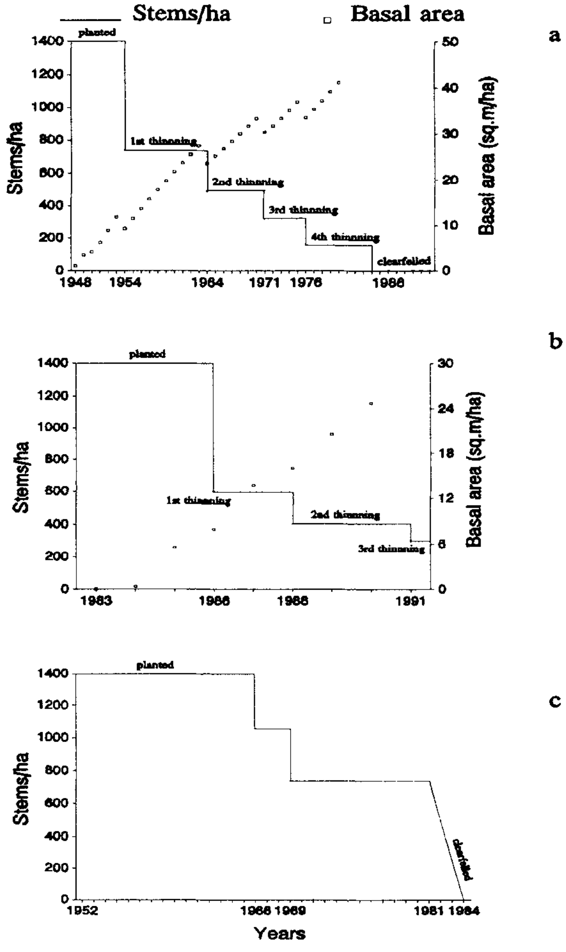

Fig. 2. Plantation treatment histories presented as stems per hectare decrease and estimated basal area increases in the catchments in Biesievlei (a), Westfalia D (b) and Cathedral Peak CII (c). The 46% thinning at Cathedral Peak CII was applied in two stages, in 1966, 40% of the area was thinned and in 1969, a further 46% was thinned.

bedrock is a biotite-bearing granite gneiss (the Turfloop granite) with dykes and sills of diabase criss-crossing the catchment area. The soils on the slopes are deep and well-drained laterites, changing to hydromorphic soils in the riparian zone. Generally, the soils are friable and well-aerated (Döhne, A., 1984. Soil survey (AD7) of the Westfalia conservation catchments. Unpublished report. Dept. of Environmental Affairs. Sabie FRC.). The indigenous vegetation of the area is transitional between evergreen high forest and deciduous woodland. A detailed description of the catchments is given by Smith and Bosch (1989).

Cathedral Peak also lies in the summer-rainfall area, with 84% of rainfall occurring from October to March (Bosch, 1979). The catchments are formed in basaltic lavas of the Drakensberg Basalt Group, that overlie the Clarens Sandstone. Three dolerite dykes run through the research area. The soils are deep, well-drained, red and yellow laterites. Grassland, classified as Highland Sourveld (Acocks, 1953) is the dominant indigenous vegetation, with shrubby woody communities occurring along the riparian zones (Bosch, 1979). More information is given in Table 1, Nänni (1956) and Bosch (1979).

3. Treatments

The afforested catchments in these studies were planted-up at 1370 stems ha^{-1} and, within practical limitations, thinned according to the prevailing standard departmental silvicultural prescriptions for that site quality and species (Poynton, 1977 Poynton, 1979).

At Biesievlei 98% of the catchment, including the riparian zone, was planted-up with *P. radiata* in 1948. This was followed by standard thinnings for sawlog production, illustrated in Fig. 2a, of a 46% thinning at 9 yr, 34% at 16 and 23 yr, and 22% at 28 yr. Three different Jonkershoek catchments were used to obtain the most stable calibration relationships. Both Lambrechtsbos-A and Langrivier were protected fynbos (scrub) catchments, while the Bosboukloof catchment is 57% afforested with *P. radiata* but only periods when the plantation cover was stable were used for statistical comparisons (Table 2).

Westfalia D was originally an indigenous forested catchment. In January 1981 the riparian zone was cleared, and from December 1982 to January 1983 the whole catchment was cleared by clearfelling trees and bulldozing smaller plants. It was then planted-up with *E. grandis* in March and April 1983. Thinning of the plantation followed at three (46%), five (34%) and eight years (50%) after planting (Fig. 2b). The control catchment is Westfalia B which has a stable cover of indigenous scrub forest.

The main part of the plantation in Cathedral Peak CII was planted to *P. patula* in 1952. Smaller areas were subsequently afforested, with a fire-belt being

Table 2

Details of the calibration regression models used to test for thinning effects on streamflow in the three treatment catchments

Catchment	Type of model	Thinning	Model	Intercept (β_0)	Regression coefficients	R^2
Biesievlei	Total streamflow	2nd[a]	$T=\beta_0+\beta_1C+\beta_2C^2$	0	0.262(β_1) 0.91(β_2)	0.91
		3rd[b]	$T=e^{\beta 0}C^{\beta 1}$	−0.471	1.113(β_1)	0.95
		4th[a]	$T=\beta_0+\beta_1C$	−0.345	0.885(β_1)	0.92
	Dry season streamflow	2nd[c]	$T=\beta_0+\beta_1C+\beta_2C^2$	0.242	0.253(β_1) −0.003(β_2)	0.91
		3rd[b]	$T=e^{\beta 0}C^{\beta 1}$	−0.482	1.064(β_1)	0.98
		4th[b]	$T=e^{\beta 0}C^{\beta 1}$	−0.375	0.963(β_1)	0.92
Westfalia	Total streamflow	1st	$T=\beta_0+\beta_1C+\beta_2C^2$	0.720	0.863(β_1) −0.009(β_2)	0.91
		2nd	$T=\beta_0+\beta_1C$	−0.902	0.426(β_1)	0.96
	Dry season streamflow	1st	$T=\beta_0+\beta_1C$	−0.304	1.052(β_1)	0.96
		2nd	$T=e^{\beta 0}C^{\beta 1}$	−3.456	2.134(β_2)	0.95
Cathedral Peak	Total streamflow	1st	$T=e^{\beta 0}C^{\beta 1}$	−0.727	1.114(β_1)	0.95
	Dry season streamflow	1st	$T=e^{\beta 0}C^{\beta 1}$	−0.871	1.207(β_1)	0.88

planted-up in 1965. In 1966, 40% of the plantation received a 46% first thinning (to 740 stems ha^{-1}), and in 1969, a further 46% of the plantation received the same thinning (Fig. 2c). The single control catchment used was CIV which is a grassland catchment that is burned biennially.

4. Data collection and analysis

Stream stage heights through sharp-crested compound 90° V-notch weirs were monitored continuously with autographic Belfort water level recorders. Streamflow charts were digitized and streamflow volumes summed over weekly periods and expressed as rainfall depth equivalent in millimetres.

The paired catchment method was used to test for treatment effects in the streamflow of the thinned catchments. Streamflow in each treated catchment was calibrated against that of a control catchment over a pre-treatment period. Two calibration equations were developed for each catchment: one to predict total (annual) and the second to predict dry season streamflow. The dry (low) flow season was taken as November to March (5 months) for the south-western Cape, and May to September (5 months) for the Transvaal and KwaZulu-Natal catchments. Details of the regression models that resulted from the analyses are given in Table 2. Regression models were fitted using the SAS statistical package (SAS Institute, 1985). We tested for treatment effects by adding a dummy variable to the regression models for each dependent variable (Gujarati, 1978). The F-test for the extra sum of squares explained by the resulting full model relative to the reduced model (i.e., the model without the dummy variable and its factors) is a test of the treatment. This method is described fully in Hewlett and Bosch (1984) and Hewlett and Doss (1984).

The calibration regression models were used to predict streamflow values for post-treatment periods. The difference between these predicted (or expected) values and the actual measured values, i.e., the deviations from the calibration relationship, were quantified to indicate the magnitude of any response to the

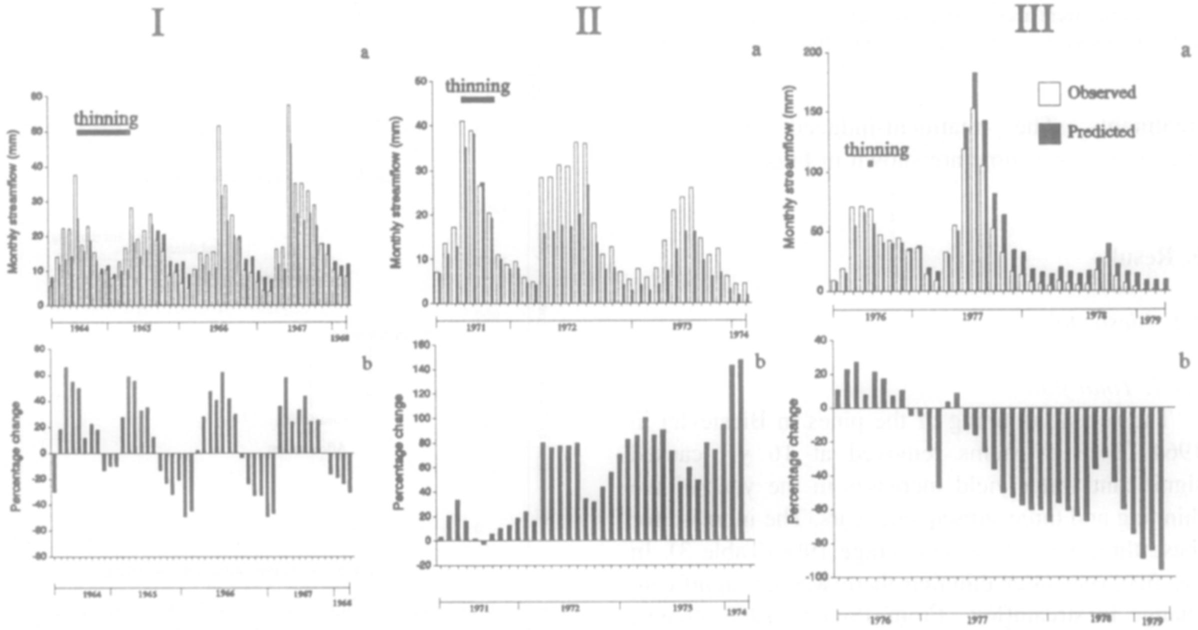

Fig. 3. (a) Monthly streamflow during and after the second (I,1964/1965), third (II, 1971/1972) and fourth (III, 1976/1977) thinnings of the Biesievlei plantation, relative to the predicted yield, and (b) the percentage change from predicted streamflow for the same periods. Hydrological year: April–March.

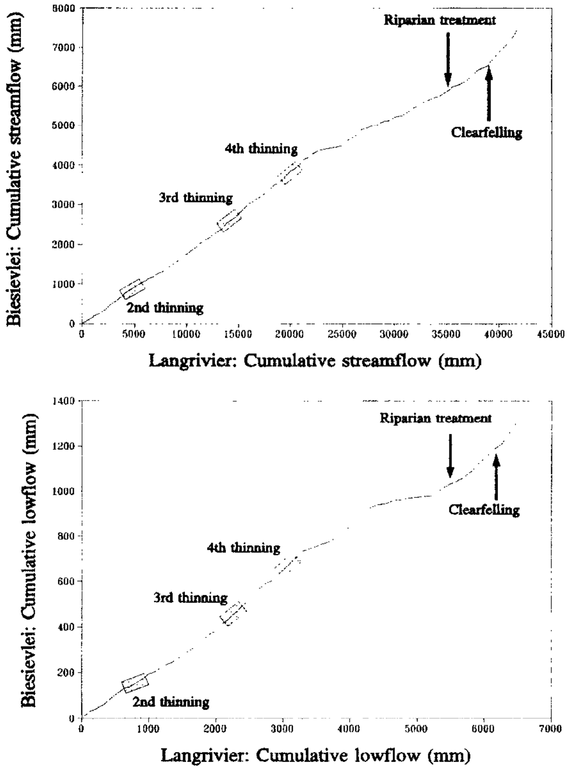

Fig. 4. Accumulated weekly streamflow for Biesievlei (treated) and Langrivier (control), with the silvicultural treatments indicated. Values were accumulated over (a) the full hydrological year and (b) the successive dry seasons (April 1961–December 1986).

treatments. The treatment-induced changes in streamflow over time are shown in Figs. 3–6.

5. Results

5.1. Biesievlei

5.1.1. Total flow

The second thinning of the pines in Biesievlei in 1964 (34% of stems removed at 16 yr) caused significant water yield increases in the year of the thinning and three subsequent years. The increase for these three years was on average 19% (Table 3). In the first year after thinning there was no significant change in streamflow. From 1964 to 1968 streamflow increased by a total of 112 mm (Table 3). From monthly comparative streamflow plots it is clear that these increases were recorded mainly during the wet season (Fig. 3 Ia). It would seem that the increase during the first wet season following the thinning was cancelled by equal reductions during the dry period of that same year. These effects are clearly seen in the positive and negative percentage changes (Fig. 3 Ib). In a double mass plot of Biesievlei streamflow against that of an alternative control catchment, Langrivier, there is no perceptible change in the slope after the second thinning (Fig. 4).

The third thinning (34% at age 23) resulted in increased streamflow during that year, and the two years following. Unlike the second thinning, the increases were spread over the whole hydrological year (Fig. 3 II). Although there was only a 10% increase during the year of the thinning, the average increase for the following two years was 68% (Table 3). This amounted to a 181 mm increase in total

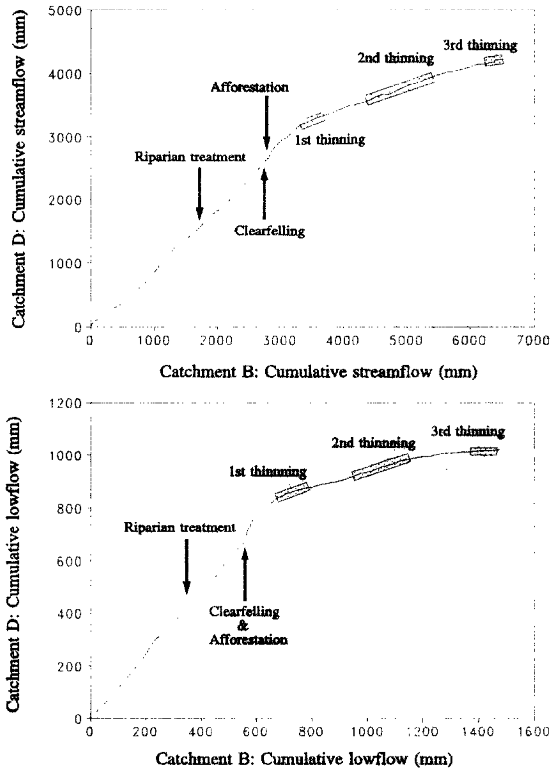

Fig. 5. Accumulated weekly streamflow for Westfalia catchments D (treated) and B (control), with the silvicultural treatments indicated. Values were accumulated over (a) the full hydrological year and (b) the successive dry seasons. (October 1977–September 1991).

streamflow over the three year period (including the year of the thinning). Treatment effects did not continue into the third post-thinning year. In the double mass plot (Fig. 4), the increase in Biesievlei streamflow can be seen in a small increase in slope after the third thinning, that is more-or-less maintained until the fourth thinning.

The fourth thinning in Biesievlei (22% at age 28) was followed by a marked and significant decrease in water yield (Table 3, Fig. 3 III). During the year of the thinning itself there was a small and not statistically significant increase of 35 mm in streamflow, but over the next two years the total decrease was 328 mm (Table 3). This surprising result is difficult to explain as the trees were already 28 yr old, and neither a vigorous nor rapid growth response to the thinning seemed likely. Inspection of the predictive relationship, indicated that the exceptionally high rainfall for the two years after the treatment (1976 and 1977) might have caused the two catchments to respond differently, in effect invalidating the calibration relationship ($R^2 = 0.92$; Table 2). Therefore an alternative calibration model, using the Langrivier catchment as control, was tested and gave small increases (15% and 19% respectively) for the year of the thinning and the following year. However, for the second post-thinning year (1978) the large decrease (58%) in streamflow was confirmed. This marked reduction in Biesievlei streamflow after the fourth thinning is shown as a strong decrease in slope in the double mass plot of Biesievlei against Langrivier (Fig. 4).

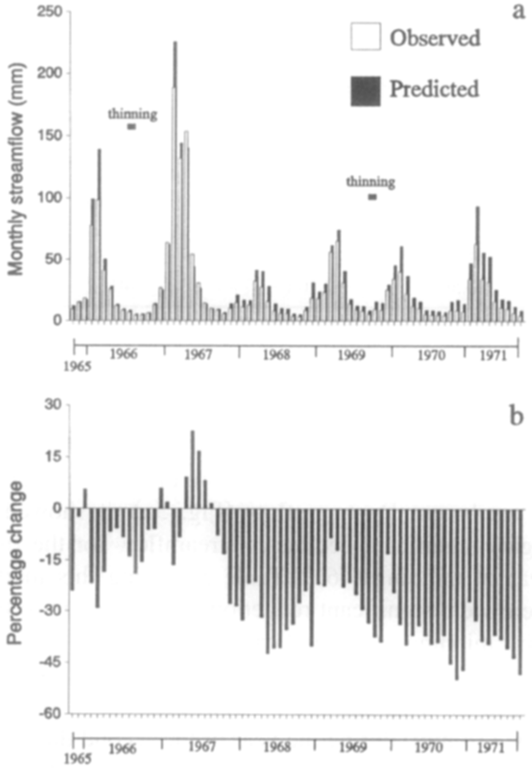

Fig. 6. (a) Monthly streamflow during and after the two partial thinnings (1966 and 1969) of the pine plantation in Cathedral Peak CII relative to the predicted flow, and (b) the percentage change from predicted streamflow for the same period. Hydrological year: October–September.

5.1.2. *Dry season streamflow*

As dry season flows are particularly important, separate models were constructed for the low flow season alone (Table 3). The regression models established on dry season flows generally confirmed the results obtained from the total yield models. The double mass plot against Langrivier low flows is also very similar to that for total flow (Fig. 4). Following the second thinning, dry season flows were (16–25%) lower than expected in the year of thinning and the two subsequent years (Table 4). This confirmed the impression observed in the total flow analysis (Fig. 3 IIa). Following the third thinning there were substantial increases (22–99%) in flow during the dry season in all three years (Table 4), which was in agreement with the findings of the total flow model (Table 3). The relative increases though were greater in the dry season.

During the fourth and final thinning there was a significant increase of 26 mm in dry season flow that constituted most of the increased streamflow for that year. In subsequent years, declining trends in low flow similar to those predicted for the full year were recorded (Tables 3 and 4).

5.2. *Westfalia*

5.2.1. *Total flow*

Following the afforestation of Westfalia catchment D with *E. grandis* growth was extremely rapid, and the effect of afforestation on streamflow marked. This is illustrated in the double mass plots for both

Table 3
Changes in weekly and equivalent annual streamflow in the treated catchments. Significance level for treatment effects, except where indicated as non-significant was 0.0001

Catchment	Description of treatment or period	Period of analysis	No. of weeks	Observed mean weekly streamflow (mm)	Change in weekly streamflow (mm) relative to model prediction	Change in annual streamflow (mm a^{-1})
Biesievlei	Calibration	April 1961–March 1964	157	5.54		
	2nd thinning	April 1964–March 1965	52	3.80	0.70 (23%)	36.50
	post-thinning (1)	April 1965–March 1966	52	3.58	0.10 (3%)^{NS}	4.94
	post-thinning (2)	April 1966–March 1967	52	4.07	0.56 (16%)	28.89
	post-thinning (3)	April 1967–March 1968	53	5.32	0.78 (17%)	41.50
	Calibration	April 1969–March 1971	104	4.57		
	3rd thinning	April 1971–March 1972	52	3.94	0.37 (10%)	19.12
	post-thinning (1)	April 1972–March 1973	53	4.79	1.87 (64%)	99.04
	post-thinning (2)	April 1973–March 1974	52	2.92	1.21 (71%)	63.01
	Calibration	April 1974–March 1976	104	6.50		
	4th thinning	April 1976–March 1977	52	9.02	0.67 (8%)^{NS}	35.03
	post-thinning (1)	April 1977–March 1978	52	11.51	−4.01 (−26%)	−208.59
	post-thinning (2)	April 1978–March 1979	52	1.84	−2.26 (−55%)	−119.85
Westfalia D	Calibration	October 1983–September 1985	105	4.25		
	1st thinning	October 1985–September 1986	52	3.13	−2.71 (−46%)	−140.79
	Calibration	October 1986–September 1987	52	3.41		
	2nd thinning	October 1987–September 1988	51	7.62	0.27 (3%)^{NS}	13.55
	post-thinning (1)	October 1988–September 1989	50	2.65	−0.08 (−3%)^{NS}	−4.11
	post-thinning (2)	October 1989–September 1990	48	2.52	−0.91 (−27%)	−47.52
Cathedral Peak	Calibration	October 1962–September 1965	156	7.67		
	1st thinning (40%)	October 1965–September 1966	53	6.12	−1.51 (−20%)	−80.25
	post-thinning (1)	October 1966–September 1967	52	13.55	−0.37 (−3%)^{NS}	−19.07
	post-thinning (2)	October 1967–September 1968	52	3.02	−1.33 (−31%)	−68.99
	1st thinning (46%)	October 1968–September 1969	52	5.09	−1.26 (−20%)	−65.54
	post-thinning (3)	October 1969–September 1970	52	3.55	−1.67 (−32%)	−86.56
	post-thinning (4)	October 1970–September 1971	52	4.56	−2.70 (−37%)	−140.52

total and dry season flow (Fig. 5). The dynamically changing relationship between the treatment and control catchments made it difficult to obtain a calibration relationship with which to test thinning effects in this vigorous plantation. Although such calibrations were developed (Tables 3 and 4) they were of limited value, and the double mass plots are probably more informative.

After the clearfelling of the indigenous forest in catchment D, there was a slight increase in streamflow (Fig. 5a) that lasted for two years (Bosch and Smith, 1989). After afforestation there was a definite decrease in streamflow. The reduction in streamflow become more obvious after the first thinning (Fig. 5a) just three years after the establishment of the plantation.

A calibration model was obtained for the two hydrological years before the first thinning (Table 3). As this was the period just before the sudden change in catchment D streamflow (Fig. 5a), it showed a highly significant decline in streamflow for the first year of thinning (46%; Table 3). Using this model there were significant reductions right through to the third thinning. A second calibration relationship was established using the year before the second thinning (Table 3). This showed a slight increase in streamflow (14 mm) during the year of the second thinning. There was no significant change in the year following the second thinning but a significant decrease of 27% from the predicted in the second year (Table 3). The third thinning was not investigated as the stream dried up just after the treatment. Thinnings in this

Table 4

Changes in weekly flows during dry seasons and equivalent seasonal streamflow in the treated catchments. Significance level for treatment effects, except where indicated as non-significant was 0.0001

Catchment	Description of treatment or period	Period of analysis	No. of weeks	Observed mean weekly streamflow (mm)	Change in weekly streamflow (mm) relative to model prediction	Change in defined low flow period (mm)
Biesievlei	Calibration	November 1961–March 1964	44	2.45		
	2nd thinning	November 1964–March 1965	21	2.65	−0.52 (−16%)	−10.89
	post-thinning(1)	November 1965–March 1966	21	1.92	−0.64 (−25%)	−13.46
	post-thinning(2)	November 1966–March 1967	21	1.65	−0.37 (−18%)	−7.74
	Calibration	November 1969–March 1971	43	2.11		
	3rd thinning	November 1971–March 1972	21	1.91	0.34 (22%)	32.86
	post-thinning(1)	November 1972–March 1973	22	2.01	0.83 (70%)	18.17
	post-thinning(2)	November 1973–March 1974	22	1.74	0.87 (99%)	19.04
	Calibration	November 1974–March 1976	44	2.70		
	4th thinning	November 1976–March 1977	21	6.63	1.24 (23%)	25.99
	post-thinning(1)	November 1977–March 1978	21	2.32	−1.94 (−45%)	−40.61
	post-thinning(2)	November 1978–March 1979	22	0.60	−1.65 (−73%)	−36.24
Westfalia D	Calibration	May–September 1985	22	3.76		
	1st thinning	May–September 1986	22	1.92	−3.63 (−65%)	−79.76
	Calibration	May–September 1987	22	1.37		
	2nd thinning	May–September 1988	21	3.40	−1.79 (−34%)	−37.59
	post-thinning(1)	May–September 1989	20	0.77	−0.21 (−23%)	−4.12
	post-thinning(2)	May–September 1990	22	0.75	−0.86 (−53%)	−18.81
Cathedral Peak	Calibration	May 1963–September 1965	65	3.01		
	1st thinning (40%)	May–September 1966	22	1.73	−0.18 (−9%)	−3.84
	post-thinning(1)	May–September 1967	22	5.44	0.35 (7%)^{NS}	7.76
	post-thinning(2)	May–September 1968	22	1.86	−1.31 (−41%)	−28.86
	1st thinning (46%)	May–September 1969	22	3.14	−1.25 (−28%)	−27.42
	post-thinning(3)	May–September 1970	22	1.39	−0.79 (−36%)	−17.31
	post-thinning(4)	May–September 1971	21	2.29	−1.68 (−42%)	−35.21

eucalypt plantation thus did not cause any substantial increase in streamflow, and this is apparent from both double mass curves (Fig. 5).

5.2.2. Dry season streamflow

As is clear from Fig. 5, the dry season flow followed a similar trend to that of the total flow, though the increase in streamflow in Westfalia D after the clearfelling is more noticeable in the plot of cumulative dry season flow (Fig. 5b). The decrease after the first thinning is much more marked (65%) than that for the total flow (46%), the reductions in low flows contributing roughly half the recorded reduction for that year (Table 4). During the second thinning the dry season streamflow decreased significantly, though this effect was hidden in the analysis of the full year (Tables 3 and 4). In successive years, low flow was increasingly reduced below that which was expected. Clearly, the reduction in dry season flow contributed substantially to the change in the streamflow of Westfalia catchment D. The thinnings did not result in any notable change in the dry season streamflow.

5.3. Cathedral peak

5.3.1. Total flow

At Cathedral Peak, though less of the catchment was afforested and growth rates were slower than at Westfalia, the thinnings took place at a time when the tree growth rate was at its highest and the effect of trees on streamflow was changing each year. The other complication at Cathedral Peak was that the single first thinning operation was spread over two periods, three years apart, making it more difficult to measure a definite streamflow response to thinning. The strong downward trend in annual water yield was little affected by the thinnings and made the measurement of any effect difficult.

The streamflow in CII at Cathedral Peak (Fig. 6) showed very similar trends to that recorded in Westfalia catchment D. From the first partial thinning of the plantation in 1965/1966 through to 1971, there were significant reductions in streamflow each year, except in 1966/1967 (Table 4). The thinnings might have slowed-down the rate of decrease in streamflow, seen in the reduced percentage decrease (20% as opposed to 30% or more) during each year of a thinning. It did' however, not have enough of an effect to reverse the overall trend of declining streamflows.

5.3.2. Dry season streamflow

From the low flow models there is some indication that the reductions in low flow were smaller in the year immediately following thinning (Table 4). The streamflow during the first partial thinning year and the year following (1966 and 1967) was not significantly affected by the thinning (Table 4). After that the reductions in flow consistently exceeded 35% of the expected seasonal flow, except for the second partial thinning year (1969; Table 4) when the reduction was 28%. The dry season flow reductions were higher (32% on average) than the average reduction of 28% in total streamflow (Table 3).

6. Discussion

6.1. Total streamflow

A marked reduction in the stand density of a plantation can be expected to cause an immediate reduction in total transpiration from the plantation. Reduction in the canopy cover would also result in a decrease in interception losses, resulting in more water reaching the soil. This in turn would lead to a wetter catchment and an increase in streamflow. At Biesievlei both the second and third thinnings resulted in increased streamflow. Although basal area reductions were very similar in both thinnings (Fig. 2a), the increase in streamflow after the third thinning was double that of the second thinning. The increase following the second thinning was less than that estimated by van der Zel (1970) for the same thinnings, but was calculated over a different period and using a different method. Both thinnings caused flow increases that only lasted for the first two to three years following the treatments. The calculated basal area for the plantation three years after each thinning (Fig. 2a) shows that the basal area rapidly recovered to pre-thinning levels. Studies on the growth response of *P. radiata* in the western Cape showed that thinning increased the length and width of the canopies of the remaining trees (van Laar, 1979). This implies a full recovery of leaf area index and, consequently, interception losses in the thinned stand. Trees that remain after thinning would make use of the extra available moisture, restricting the potential increase in streamflow over time. In a thinning experiment on loblolly pine (*Pinus taeda*) in Oklahoma, Stogsdill et al. (1992) showed that throughfall was positively related to the degree of thinning, and water use from plots (excluding interception) was, in turn, positively related to the available soil water during the first two years after thinning.

The final thinning at Biesievlei that produced the anomalous result of a reduction in streamflow occurred just before two exceptionally wet years. Vapour losses measured in catchment experiments have been shown to be higher in wet years (Turner, 1991; Ruprecht et al., 1991; JM Bosch, personal communication, 1994). This could account for streamflow being less than predicted in the wet years. The catchment used as control was only 57% afforested compared to the 98% of Biesievlei. A smaller increase in transpiration in the control (less reduction in streamflow) could have caused an overprediction of streamflow in Biesievlei. The relative flow reduction in Biesievlei for these years, especially 1976/1977, was also evident in the study by van Wyk (1987) where he used a rainfall driven prediction model. A possible mechanism for this phenomenon might be that a greater proportion of the rainfall in the catchments with a greater proportion of plantation went into recharging soil–water storage. These effects overshadowed any influences that the fourth thinning might have had on streamflow.

At Cathedral Peak CII, the pine plantation started reducing streamflow from about 1958, eight years after planting (Bosch, 1979). As with the plantation at Biesievlei, the decrease levelled off about 17 yr after afforestation, in 1967/1968. This meant that the calibration period, the first partial thinning and two years following all fell within the period where the streamflow was still adjusting to the water use demands of the developing plantation. Streamflow decreased on average by an additional 50 mm each year from 1958/1959 to 1967/1968. The two partial thinnings did not substantially reduce this decrease. Bosch (1979) reached similar conclusions.

The eucalyptus plantation at Westfalia D is another example of how the development of a plantation may dominate the observed streamflow, masking the effects of thinnings. The reduction in streamflow commenced three years after afforestation and reached an average of 300 mm a^{-1} (Bosch and Smith, 1989). The calculated basal area of the plantation (Fig. 2b) on an annual basis is only slightly affected by the thinnings. Similarly, leaf area index, to judge from measurements in comparable young and vigorous *E. grandis* stands (Dye et al., 1995), is likely to have been close to a maximum of 4 by three years and would have recovered to maximum levels within a year of each of the thinnings. Another possible factor contributing to the absence of a response to thinning, is that the highest rainfall occurs at the time of the summer growing season, so that water availability coincided with water demand by the trees. The growth of the remaining trees during the year of the thinning was apparently such that their water use neutralised the effect of the removal of 40% of the stems.

These results are comparable to those obtained in the eucalypt and pine afforested Mokobulaan catchments A and B in the Mpumalanga Province, South Africa, (Scott and Lesch, in press) where the influence of thinnings was masked by the rapid decline in water yield caused by the fast growing plantations.

It is possible that more refined methods of assessing the effect of thinning on the hydrology of a plantation would have shown noticeable changes to have occurred. Such methods could have included soil–water monitoring, measurement of through-fall in a reduced canopy, or measurement of streamflow at a finer scale, such as the two-hourly interval during dry months as employed by van der Zel (1970). The thinnings that were applied in these experiments were selective: removing the worst stems and slowest growing trees. Unselective methods such as strip or row thinnings may well have caused more noticeable impacts on catchment runoff.

The homeostasis hypothesis referred to earlier (Whitehead et al., 1984) appears to fit the experimental results obtained here. In Jonkershoek, where pines are grown on a longer rotation for sawlogs and where thinnings were applied to older stands, water use in the catchment returns to pre-thinning levels within three years. In the summer-rainfall sites, the timber stands at the time of thinning had yet to achieve equilibrium with the site. On these sites the effect of thinning was both hidden within the dominant trend of diminishing streamflow as a result of afforestation, and too small to be detected by the paired catchment method. It seems likely that spare capacity in the unsaturated soil water stores of the latter catchments absorbs any short-term savings in water use such as might be caused by a thinning.

7. Dry season streamflow

The only thinning to increase streamflow in the dry season significantly was that of the third thinning of Biesievlei. In the other experiments, low flows were dominated by the streamflow reductions experienced by the rapidly growing plantations. The greatest reduction was at Westfalia D where the reduction in low flow accounted for roughly 50% of the annual decrease in streamflow after the first thinning.

8. Conclusions

Thinning of roughly one third of the stems in a maturing pine plantation in the winter rainfall area led to streamflow increases in the year of thinning and for two to three subsequent years. The size of increase was highly variable, ranging between 10 and 71% or 19 and 99 mm a^{-1} in individual years. Increases did not persist beyond the third post-thinning year. In the mature pine plantation, there is some evidence that the relative increase in the dry season flow was greater than that recorded over the full year, indicating that it was possibly the reduction in transpiration that caused a large part of the hydrological response to thinning.

In other younger pine and eucalypt plantations under a summer-rainfall regime, the results indicate that any savings in water use caused by thinning were insufficient to reverse the downward trend in streamflow following afforestation. In plantations of fast-growing species with short rotations, such as eucalypt plantations, there is unlikely to be an observable increase in streamflow following thinning as the high growth rate and rapidly increasing water consumption predominate. Additional soil-water that should become available following thinning did not appear to reach the streams in the cases studied, and probably served simply to replenish depleted stores of soil-water.

The paired catchment method was unable to measure an integrated catchment response to thinning in these vigorously developing plantations. More refined methods would be needed to asses the effect of thinnings on water partitioning in such plantations.

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