Preliminary empirical models to predict reductions in total and low flows resulting from afforestation

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Abstract

Mathematical models to predict runoff reductions due to afforestation are presented. The models are intended to aid decision-makers and planners who need to evaluate the water requirements of competing land uses at a district or regional scale.

Five afforestation catchment experiments were analysed by the paired catchment method to determine the reductions in both total (annual) and low flows. The percentage reduction in flow after afforestation with both eucalypts and pines was determined for each post-treatment year relative to the expected flow based on a calibration relationship with an untreated (control) catchment. We fitted curves to these data points to predict the effects of afforestation under optimal and sub-optimal growing conditions. Eucalypt plantations were found to deplete both total and low flows sooner and in larger quantities than pine stands.

Introduction

Since 1972 the Forest Act has required timber growers to apply for permits to establish commercial plantations on new land or sections of land which, after harvest, have not been planted to trees for a period exceeding five years (Van der Zel, 1990). Such applications may be rejected on the grounds that afforestation would use an unacceptably high proportion of water in the catchment. In considering the permit applications the affect of afforestation has been estimated by means of the so-called Van der Zel curves (Van der Zel, 1995) which are a generalisation, using additional data, of an original curve developed from a single catchment experiment at Cathedral Peak by Nänni (1970). Although very useful, this model is based on limited local data and only accounts for total streamflow reductions, while the reductions in low flow might be of more relevance to decision-makers.

Bosch and Hewlett (1982), in their review of 94 catchment experiments, estimated that mature pine and eucalypt forest types cause 30 to 40 mm change in water yield per 10% of the catchment subjected to change in cover. For example, the clearfelling of a mature pine forest occupying 20% of a humid grassland catchment could be expected to increase streamflow by 60 to 80 mm·a^{-1}. Another important consideration is the effect of afforestation on low flows, as it is during the dry period immediately prior to the rainy season that a reliable water supply is most critical for downstream or run-of-river water users. Although afforestation is known to cause significant reductions in both total flows (Nänni, 1970; Van Lill et al., 1980; Bosch and Hewlett, 1982; Van Wyk, 1987; Bosch and Smith, 1989; Smith, 1991) and low flows (Banks and Kromhout, 1963; Bosch, 1979; Keppeler and Ziemer, 1990; Smith and Scott, 1992b), the impact of afforestation on low flows may differ both in relative amount and timing (within the rotation) from that on total flows. Should the impact of afforestation be relatively greater on low flows than on total flows, then it would make more sense to consider reductions in low flow rather than total flow as a guideline for afforestation permit allocations.

Results from earlier forest hydrology studies in South Africa indicate that the water use characteristics of eucalypts and pines may be quite different. Eucalypts appeared to have an earlier influence on water yield than afforestation with pines, and streamflow reductions due to the eucalypt plantings were apparently larger than those caused by the pines (Van Lill et al., 1980; Bosch and Smith, 1989). This would indicate that different afforestation guidelines may be required for different commercial tree types.

There is, therefore, a need for an improved model that may be used as a guideline for decision-making and planning regarding afforestation effects. The model should provide an estimate of reductions in both low flow and total flow which will occur with varying degrees of afforestation, and should differentiate between pine and eucalypt plantings should differences in streamflow response to these tree types be significant. This paper reports on the analyses of five experiments measuring the effects of afforestation on water yield, and on our efforts to produce generalised models of the observed effects that will fill the needs described above.

Methods

The effects of afforestation on streamflow for five South African research catchments were determined by the paired catchment approach. The catchments were selected to cover, as far as possible, the geographical range of South African forestry (Fig. 1), and to include both species groups for which there are experimental catchments.

One pair of catchments is located on the Westfalia estate (catchment D afforested, catchment B control) near Tzaneen in the Northern Province (23°43'S, 30°04'E); two at Mokobulaan (catchments A and B afforested, catchment C control) situated SE of Lydenberg on the Mpumalanga escarpment (25°17'S; 30°34'E); a fourth at Cathedral Peak (catchment III afforested, catchment IV control) near Winterton in the KwaZulu-Natal Drakensberg (29°00'S; 29°15'E), and the final pair within the Jonkershoek Valley (Lambrechtsbos-B afforested, Bosboukloof control) near Stellenbosch (33°57'S; 18°15'E), in the Western Cape Province. Some catchment characteristics are summarised in Table 1.

In the case of the Cathedral Peak and Mokobulaan experiments the control catchments are grasslands, burned on a regular two-year cycle. In the case of Westfalia the control catchment is scrub forest, over 50 years old at the time of the experiment, slow-growing and with a stable relationship between rainfall and runoff. At Jonkershoek, the 57% afforested Bosboukloof provided the best of several possible controls. The period (1960 to 1980)

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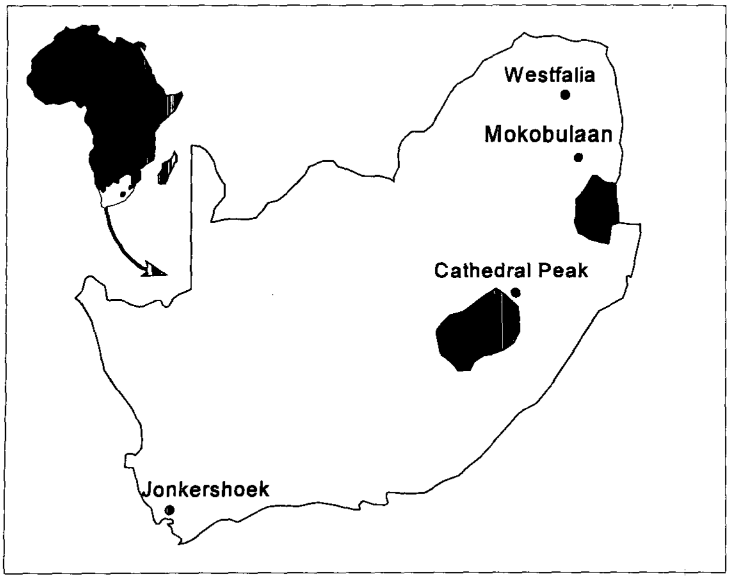

Figure 1
The general location of the forestry catchment experiments used in this study

used in the paired catchment comparison was when the pines in Bosboukloof were mature and, although subject to periodic silvicultural treatments in minor parts of the plantation area, the effect of pines on streamflow remained relatively stable (Van Wyk, 1987).

Two of the sites were afforested with *Eucalyptus grandis* (Mokobulaan A and Westfalia), two with *Pinus patula* (Mokobulaan B and Cathedral Peak) and the last site with *P. radiata* (Jonkershoek). *Eucalyptus grandis* and *Pinus patula* are the two most widely planted timber species in South Africa, these two species comprising 63% and 49% of all hardwood and softwood plantings respectively (DWAF, 1996). *Pinus radiata* is the species of choice in the Western Cape Province and makes up 8.7% of all South African softwood plantings (DWAF, 1996). In terms of species, therefore, these experiments are fairly representative of commercial forestry in this country. All sites were planted and tended according to the then standard Department of Forestry prescriptions. This means that there was no site preparation (ploughing or ripping) or fertilisation but that seedlings were planted into pits in a cleared ring or roughly 1 m diameter. Further details on the sites, experimental layout and early results from these catchment studies may be found in Bosch (1979), Van Lill et al., (1980), Van Wyk (1987), Smith and Bosch (1989) and Bosch and Smith (1989).

The paired catchment approach was selected as the most reliable means of assessing the effect of land-use treatment on streamflow because it compensates for the differing effects of external influences such as 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 provided that the vegetation of these catchments remains the same or changes in a similar fashion. The streamflow measurement period prior to the afforestation of the treated catchment is referred to as the calibration period. For this period, we regressed monthly streamflow totals from the treated catchment against those of the control catchment. A statistical test of the treatment (afforestation) is provided by the dummy variable method (Draper and Smith, 1966). Afforestation effects were measured as the difference between the expected streamflow (based on the derived calibration relationship) and the observed streamflow measurements.

We tested several models to express the relationship between flows in the treated and control catchments during the calibration periods. Model selection was done on the basis of R^2 and an inspection of residuals. Good calibration models were obtained with little unexplained variation in the treatment catchment streamflow (Smith and Scott, 1992), though models for the total flow were superior to those for low flow. The best of these calibration models (one each for total and low flows in each of the treatment catchments) were then used to predict what the flows would have been had the catchments not been afforested. The decrease in flow from the treated catchments for each hydrological year after treatment was also expressed as a percentage of this predicted or expected flow.

Low flows were defined roughly as the driest three months of an average year or, more specifically, as those monthly flows below the 75th percentile exceedance level. All monthly flows in the control catchment were ranked to find the flow that was exceeded 75% of the time over the whole record. All months with a flow below this level in the control catchment were included in the low-flow data set.

TABLE 1
SOME CHARACTERISTICS OF THE GAUGED RESEARCH CATCHMENTS USED IN THIS STUDY

Catchment	Area (ha)	Vegetation treatment	Mean elevation (m)	Slope[1]	MAP[2] (mm)	Virgin MAR[3]	Growth Zone[4](mm)
Westfalia B (control)	32.6	scrub forest	1 312	0.42	1 597	543	O
Westfalia D	39.6	*Eucalyptus grandis* 100%	1 165	0.33	1 611	548	O
Mokobulaan A	26.2	*Eucalyptus grandis* 100%	1 354	0.23	1 135	244	O
Mokobulaan B	34.6	*Pinus patula* 100%	1 396	0.22	1 135	217	O
Mokobulaan C (control)	36.9	grassland	1 427	0.26	1 186	143	O
Cathedral Peak CIII	138.9	*Pinus patula* 86%	2 081	0.38	1 564	648	S
Cathedral Peak CIV (control)	94.7	grassland	2 035	0.35	1 420	742	S
Lambrechtsbos-B	65.5	*Pinus radiata* 82%	683	0.46	1 473	531	S
Bosboukloof (control)	200.9	*Pinus radiata* 57%	670	0.26	1 296	593	S

[1] Slope = (I L) / A where I = contour interval (m), L = total length of contours in catchment (m), A = catchment area (m^2)
[2] Mean annual precipitation
[3] Mean annual runoff
[4] Growth zone: O = optimal, S = sub-optimal

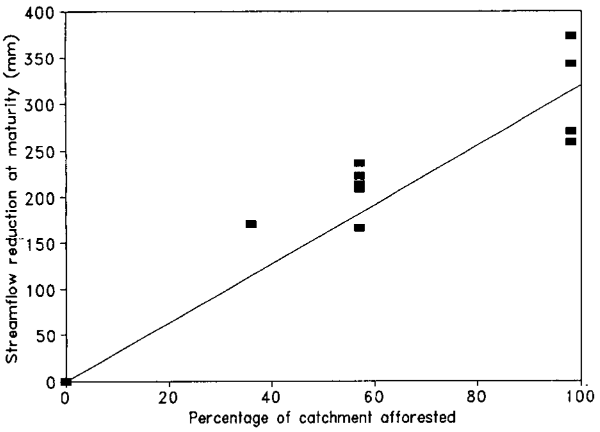

Figure 2
Averaged annual streamflow reductions plotted against the proportion of the catchment which was afforested to pine in Jonkershoek (data from Van Wyk, 1987)

Different proportions in each treatment catchment had been afforested (from 82% to 100%). Some adjustment to the results was therefore needed to account for the difference caused by these varying extents of afforestation. A previous set of results from the afforestation experiments in Jonkershoek (Van Wyk, 1987) had indicated that the relationship between the proportion of a catchment that is afforested and the resultant reductions in streamflow may not be simply linear (Fig. 2). The afforested part of a catchment, within limits, may be able to exploit a greater portion of the single catchment than it physically occupies. However, insufficient data exist to allow a reasonable estimate of this effect to be made, so a simple linear relationship was assumed. The measured reductions in streamflow were adjusted linearly therefore to give comparable reductions assuming that 100% of each catchment had been planted.

Streamflow reductions are very variable from year to year, being a function of both plantation age and the availability of water. In wet years larger flow reductions are measured while in dry years reductions are small. By expressing the flow reductions as a percentage of the expected flow much of the year-by-year variation caused by climatic fluctuations is removed, making it possible to fit general curves to the data.

The percentage streamflow reductions was plotted against the age of the plantation. Finally, models of relative flow reduction as a function of plantation age were fitted to these data points (Spain, 1982) for the two tree types, and for total and low flows separately.

Results

The estimated actual reductions in both total and low flows from the five afforested catchments are given in Table 2. As can be seen there is considerable variability between absolute flow reductions in successive years. The effect of afforestation with eucalypts is obviously greater than that of pines at the same age. Apart from this the pattern of flow reductions is clearly erratic.

Once expressed as percentage reductions in flow, the data are more amenable to modelling. The results from the two disparate catchments planted to eucalypts could be pooled, as could the

TABLE 2
THE REDUCTIONS (mm) IN TOTAL AND LOW FLOWS CALCULATED FOR FIVE AFFORESTED CATCHMENTS IN VARIOUS REGIONS OF SOUTH AFRICA. THE REDUCTION IS THE DIFFERENCE BETWEEN THE EXPECTED FLOW (BASED ON THE CALIBRATION RELATIONSHIP) AND THE RECORDED FLOW.

Age (yrs)	Cathedral Peak III		Lambrechtsbos-B		Mokobulaan A		Mokobulaan B		Westfalia D	
	Annual	Low	Annual	Low	Annual	Low	Annual	Low	Annual	Low
1	0	0	0	0	0	0	0	0	0	0
2	0	0	9.39	0	0	27.6	0	4	0	0
3	0	0	10.43	3.8	0.8	61.3	9.4	3.4	129.6	56.4
4	0	0	46.6	1.95	102.8	60.7	25.4	15.4	343.0	197.2
5	0	0	63.3	·	118.4	·	115.6	17.9	505.9	215.8
6	0	0	117.0	24.5	332.6	71.2	129	41.3	648.9	119.5
7	0	0	146	16.7	316.2	74.6	148.3	36.6	445.8	244.1
8	0	5.05	119	35.6	373.6	68.9	185.9	66.6	502.2	162.9
9	30.5	6.14	101.8	36.3	275.0	149.5	98.4	64.6		
10	261.4	14.8	190	48.5	378.0	105.4	136.6	66.0		
11	153.1	14.6	308.5	38.4	131.2	148.3	133.1	46.5		
12	182.5	28.1	238.6	19.0	161.4	118.8				
13	216.2	10.5	140.6	8.8	169.2	122.9				
14	421.7	6.9	282.6	·						
15	521.6	21.6	294.8	30.4						
16	310	7.1	373.1	49.5						
17	545.7	28.3	49.2	18.3						
18	1 365.5	18.7								
19	639.0	21.6								
20	614.3	28.2								
21	639.7	·								
22	685	36.5								
23	444.5	42.6								

· denotes a year when no monthly flow was low enough to classify as low flow (see Smith and Scott, 1992b)

TABLE 3
THE COEFFICIENTS AND STATISTICS TO MEASURE GOODNESS-OF-FIT FOR EACH OF THE ANNUAL AND LOW FLOW MODELS FOR BOTH PINE AND EUCALYPTS UNDER OPTIMAL AND SUB-OPTIMAL CONDITIONS

No.	Plantation type	Growth Zone	Streamflow variable	Model type *	Asymptote - A	Intercept - *ln*B	Coefficient - n	F	p>F	R^2
1.	Pine	Optimal	Annual	1	101.5	5.501	-3.251	220	0.0001	0.95
2.	Pine	Optimal	Low flow	1	101.5	4.904	-3.102	362	0.0001	0.97
3.	Pine	Sub-optimal	Annual	2	83.5	5.028	-0.382	465	0.0001	0.98
4.	Pine	Sub-optimal	Low flow	2	85.5	4.445	-0.383	387	0.0001	0.97
5.	Eucalypts	Optimal	Annual	1	101.5	4.275	-2.971	264	0.0001	0.96
6.	Eucalypts	Optimal	Low flow	1	101.5	2.528	-2.453	87	0.0001	0.89
7.	Eucalypts	Sub-optimal	Annual	1	95.0	8.972	-4.026	469	0.0001	0.98
8.	Eucalypts	Sub-optimal	Low flow	1	95.0	5.120	-2.830	409	0.0001	0.97

* Model type (Spain, 1982)
1 = sigmoidal: $Y = A/(1+BX^n)$
2 = exponential sigmoidal: $Y = A/(1+Be^{nX})$
where Y = reduction in flow (%)
A = an estimate of the maximum value for Y (asymptote)
B = intercept term
X = plantation age in years
n = exponent of X

results from two of the pine catchments, Cathedral Peak III and Lambrechtsbos-B. Data were pooled as the points were obviously clustered around common curves, and as the objective was to generalise the findings as far as possible. The data were pooled on the basis of the similarity in the results and not on the basis of geographical location or common species. This left the data from the pine-afforested Mokobulaan-B catchment as a third group to which curves were fitted.

A good fit to observed data was obtained (Models 1 to 6 in Table 3). The weakest model was that for low-flow reductions caused by eucalypts which had an R^2 of 0.89. The models that best fit these groups of percentage total and low-flow reduction data are sigmoidal. The progressive depletion of streamflow therefore appears to have the same sigmoidal form as a typical timber growth curve - an intuitively satisfactory result. The model parameters are given in Table 3, and the curves themselves are plotted in Figs. 3 and 4, for pines and eucalypts respectively.

We hypothesised that the two pairs of curves that fit the results from pine catchments reflected, as a generalisation, differences between optimal growth conditions (deep soils and subtropical climate) and sub-optimal conditions (shallow soils, higher altitudes and/or less favourable climate). Growth rates for pine are much higher at Mokobulaan than at either the Cathedral Peak or Jonkershoek sites. The Westfalia and Mokobulaan catchments are considered to be optimal forestry areas with their deep fertile soils, high rainfall (1 150 to 1 600 mm per year) and subtropical climates. The Cathedral Peak catchments, on the other hand, have shallow soils, are at high altitude and, with a less favourable climate, are sub-optimal in terms of forestry. The catchments at Jonkershoek fall somewhere intermediate to these two extremes, having a shorter growing season, but deep and moderately fertile soils. A tentative classification of forestry areas as either optimal or sub-optimal, based on Poynton's Silvicultural Map (Poynton 1971) of South Africa is given in Scott and Le Maitre (1993).

Having introduced the concept of a sub-optimal growth zone for the pines, we hypothesized that a similar pair of flow-reduction curves would exist for eucalypts growing under sub-optimal conditions. We had little basis for determining the position of such curves. But, as a start, we chose arbitrarily to increase the observed time taken for eucalypts (under optimal growth conditions) to reach a set flow reduction by the observed ratio between the times taken by pines under optimal as opposed to sub-optimal conditions to reach the same flow reductions. In this way we synthesized curves for eucalypts growing under sub-optimal conditions. This may over-estimate the effect of eucalypts under such sub-optimal conditions as eucalypts appear to be more demanding than pines in terms of site requirements. These are curves based on speculation, but they do lie between the measured bounds of fast-growing eucalypts and slow-growing pines, and we feel they are justified by their potential usefulness as an interim tool.

The flow reduction curves (models) sum up the results of the experiments and show that pines and eucalypts differ substantially in their effect on both low flows and total flows (Figs. 3 and 4). The two eucalypt afforested catchments were almost identical in their response to afforestation, showing a rapid reduction in streamflow over the first eight years until the streams dried up. The influence on streamflow of the pines under these prime conditions was slower than that of the eucalypts with the stream drying up at approximately 12 years after afforestation. The pines at Jonkershoek and Cathedral Peak caused an even more gradual reduction in streamflow, reaching scaled-up maximum total flow reductions of 90% at Jonkershoek and 80% at Cathedral Peak at approximately 16 and 22 years after afforestation, respectively. It was estimated that this point would be reached approximately 13 years after planting eucalypts in sub-optimal zones (Fig. 4).

In all the catchments the percentage flow reduction due to afforestation was greater in the low flows than in the total flows (Figs. 3 and 4). At a specific age the reduction in low flow will be greater than the reduction in total flow; or put differently, a certain percentage low-flow reduction will be reached earlier in the rotation than will the same relative reduction in total flow. As the afforested portion of a catchment is reduced, total and low-flow reductions for both species groups are expected to decline linearly.

Discussion

The observed differences between streamflow responses to plantings of eucalypts and pines are not unexpected as decreases in water yield appear to be proportional to the growth rate of a stand (Bosch and Hewlett, 1982). Eucalypts have a superior growth rate to pines in our experimental catchments and would therefore be expected to have a greater impact on streamflow than similarly aged pine stands. The streams in both of the catchments fully afforested with eucalypts dried up entirely eight to nine years after planting. Low flows dried up during October (the end of the dry season) a year or two prior to the complete drying-up of the streams, converting the perennial streams into intermittent ones. The rapid reduction in streamflow at Mokobulaan B (pines) is probably due to the highly favourable growing conditions in this region, causing a faster growth and associated decline in water yield than observed for the pines growing at Cathedral Peak and Jonkershoek. It may also be seen as a function of the lower natural water yield of this catchment.

The curves shown in Figs. 3 and 4 describe the expected percentage flow reduction in a specific year after planting. The overall effect of a full rotation of a timber crop would be assessed by summing the reductions over the full rotation and dividing by the number of years in a rotation. This is the equivalent of taking the integral of the equation describing the curve. This weighted mean reduction would also apply to a "normal" plantation, i.e. one in which there is an equal area of each age class.

Worked example

The models can be used to make quick estimates of the effect of afforestation on streamflow (see Scott and Le Maitre, 1993). For instance, if pine is to be planted as a single block (one age class) over 50% of a specific catchment that lies in a sub-optimal growth zone, the expected reduction in total flow at age X could be estimated, using Model 3 in Table 3, as:

$$\text{Total flow reduction}(\%) = 83.5/(1+e^{5.028}e^{-0.382X}) \text{ x } 50\% \text{ afforestation}$$

which at $X = 10$ years would give a 9.6% reduction in expected total flow, and at $X = 25$ years would give a 41.3% flow reduction from the whole catchment.

In the same way the reduction in low flow for this same planting at 10 years old would be:

$$\begin{aligned}\text{Low flow reduction} &= 85.5/(1+e^{4.445}e^{-0.3832(10)}) \text{ x } 50\% \text{ planting}\\ &= 15\% \text{ reduction in expected low flow}\end{aligned}$$

These models indicate that streamflow reductions are sensitive to rotation length. The longer the rotation the greater would be the mean impact of the crop and the lower the frequency of "recharge opportunities" (periods after clearfelling when evapotranspiration losses would be low). The rotation length on which timber is grown is principally determined by the intended end product: most of the eucalypts grown in Mpumalanga and KwaZulu-Natal provinces are destined for pulp or mining timber and are cut on 8 to 10 year cycles; pines grown for pulping are usually cut at around 18 years, but most sawlog rotations approach 30 years (DWAF, 1996). Thus the models would predict that the flow reductions caused by pines grown for sawlogs are likely to be similar to those caused by a shorter rotation eucalypt crop.

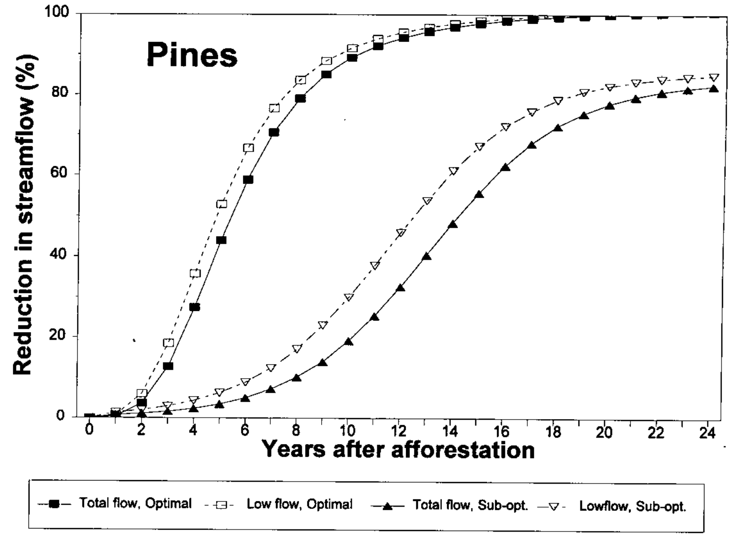

Figure 3
Generalised curves for predicting the percentage reduction in total (annual) flows and low flows as a function of age after 100% afforestation with pines

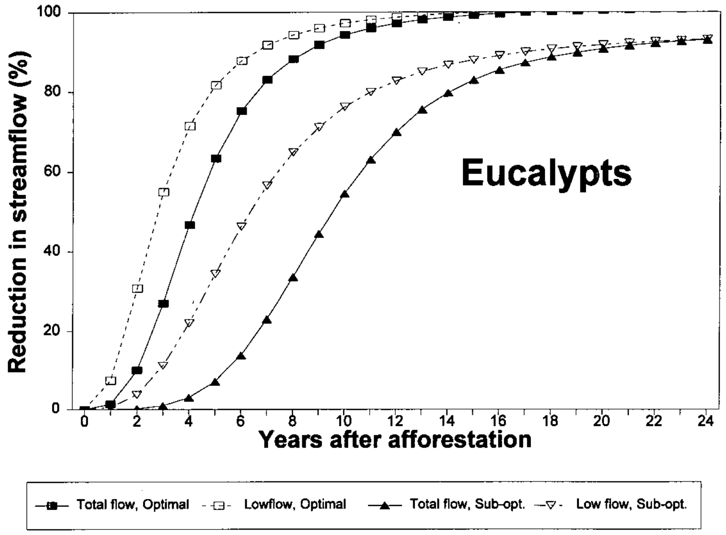

Figure 4
Generalised curves for predicting the percentage reduction in total (annual) flows and low flows as a function of age after 100% afforestation with eucalypts

Applicability of the models

In the case of the three experimental catchments where the streams dried up following afforestation (100% reductions in streamflow) these catchments had also been fully afforested. This is not a standard practice in forestry. Afforestation permits now require that zones of 30 m on either side of streams and 50 m around vleis or standing water are not planted. This limitation is based on the theory that trees in these zones will use a disproportionately greater amount of water because of its greater availability. The fact that the fully afforested catchments dried up may have something to do with the fact that the riparian zones were also planted.

The models are fitted to observed data from catchment experiments where trees were planted in pits and intended for sawlog production. Current practice for establishment of new plantations is that soils are cultivated in some way and fertilizer applied in order to stimulate a rapid initial growth. By contrast, trees planted into pits are expected to take longer to dominate the sites, and the experimental results may therefore under-estimate flow reductions under modern establishment practices. Similarly, sawlog crops are thinned periodically which will reduce canopy density and leaf area, at least temporarily. This factor would again tend to make the flow reduction models conservative.

The models presented in this paper are based on accurate data from one of the most comprehensive hydrological studies of plantation forestry. But the models remain empirical and their use in zones outside of the research areas where they were developed will constitute extrapolation. The use of proportional reductions in this study may be criticised as it implies the same relative affect of afforestation in all rainfall zones. This may be a reasonable assumption within the rainfall range of the experimental catchments but extrapolation outside of these conditions could be misleading. In particular, their accuracy in drier forestry zones (where mean annual precipitation (MAP) is, say, less than 900 mm) is uncertain. The absence of real data from these drier forestry zones is a serious problem. Any attempt to model forest water use in the lower rainfall range of forestry will remain speculative until catchment experiments are laid out in these regions.

On the other hand the research catchments used here represent a broad range of rainfall, from an MAP of 1150 mm at Mokobulaan to 1 600 mm at Westfalia and Cathedral Peak. The fact that the models fit pooled data from across this rainfall range, from a broad geographical range and, in the case of the pines, from two different species, suggests that the models are reasonably robust. Nonetheless, the models should be seen as a first effort to make generalisations from a large body of experimental results, and to provide approximate guidelines for decisions being made at the regional scale. The data for this study supplement those used in previous empirical models by Nänni (1970) and Van der Zel (1995) and give additional insight into the effects of afforestation with pines and eucalypts on streamflow. As more data become available these models can be improved, extended and verified.

Managing the effects of forestry

The effect of afforestation on low flows appears to be more marked with eucalypt plantings than with pines. This fact further justifies making a distinction between these species groups in the issuing of afforestation permits. The best means of reducing the impacts of afforestation would appear to be to reduce the proportion of a single catchment that is planted; keep the riparian or wetland areas free of trees; or shorten the rotation. At a broader scale, maintaining a normal age class distribution (equal area of each age class) within each catchment will reduce the peaks in flow reduction.

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References

BANKS CH and KROMHOUT C (1963) The effect of afforestation with *Pinus radiata* on summer baseflow and total annual discharge from Jonkershoek catchments. *For. in 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. of Hydrol.* **55** 3-23.

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.

DRAPER NR and SMITH H (1966) *Applied Regression Analysis.* John Wiley & Sons, New York. 407 pp.

DWAF (1996) Commercial Timber Resources and Roundwood Processing in South Africa 1994/95. Chief Directorate of Forestry, Department of Water Affairs and Forestry, Pretoria.

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

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.

NÄNNI UW (1970) Trees, water and perspective. *S. Afr. For. J.* **75** 9-17.

POYNTON RJ (1971) A silvicultural map of South Africa. *S. Afr. J. of Sci.* **67** 58-60.

SCOTT DF and LE MAITRE DC (1993) A Procedure for Calculating the Percentage Reductions in Annual and Low Flows for Use in the Allocation of Permits for Afforestation. Unpublished contract report, FOR-DEA 664, to the Department of Water Affairs and Forestry. CSIR Division of Forest Science and Technology, Pretoria.

SMITH RE (1991) Effect of clearfelling pines on water yield in a small Eastern Transvaal catchment, South Africa. *Water SA* **17** 217-24.

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.

SMITH RE and SCOTT DF (1992a) Simple Empirical Models to Predict Reductions in Annual and Low Flows Resulting from Afforestation. Unpublished contract report, FOR-DEA 465, to the Department of Water Affairs and Forestry. CSIR Division of Forest Science and Technology, Pretoria.

SMITH RE and SCOTT DF (1992b) The effects of afforestation on low flows in various regions of South Africa. *Water SA* **18** 185-194.

SPAIN JD (1982) *Basic Microcomputer Models in Biology.* Addison-Wesley, Reading, Massachusetts.

VAN DER ZEL DW (1990) The Afforestation Permit System. Information Leaflet no.1 issued by the Department of Environment Affairs, Private Bag X447, Pretoria.

VAN DER ZEL DW (1995) Accomplishments and dynamics of the South African afforestation permit system. *S. Afr. For. J.* **172** 49-58.

VAN LILL WS, KRUGER FJ 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. of Hydrol.* **48** 107-118.

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