Forestry and streamflow reductions in South Africa: A reference system for assessing extent and distribution

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Abstract

Forestry is an important sector of industry in South Africa but the growing of timber places significant demands on the available water resources. Yet, a ready source of information on the extent, and probable hydrological impacts, of afforestation in specific locations in South Africa has not been available. This paper reports on the modelling exercise conducted to produce an easy-to-use, handy catalogue to fill this need, and presents some of the notable results of this exercise.

Databases of quaternary catchment and magisterial district boundaries, rainfall, streamflow, forestry areas by tree genus, timber rotation lengths (years) and forestry growth potential were combined by means of a geographical information system to delineate uniform blocks of forestry. On these blocks a robust empirical model predicted total and low-flow reductions as a function of rotation length, tree genus, water availability, growth potential and plantation age distribution. The results were summarised by quaternary, tertiary, secondary and primary catchment, and by magisterial district and province.

The area of commercial timber plantations in South Africa is estimated at 1.5 million ha (57% pine, 35% eucalypts and 8% wattle), covering just 1.2% of South Africa. But the regions in which forestry is concentrated receive higher rainfall and yield a disproportionately large share of the streamflow, particularly low flow (dry-season flow). The commercial plantations are estimated to reduce mean annual streamflow by 3.2% (1 417 x 10^6 m^3) and low flows by 7.8% (101 x 10^6 m^3/yr). Our estimate of an average reduction of 98.6 mm/yr per unit of planted area is 13% lower than the previous nation-wide estimate (113.6 mm/yr) of the net effect of forestry on total water resources (DWA, 1986). Mpumalanga Province with the highest concentration of forestry (7.2% of land area) experiences the largest reductions in flow - almost 10% of total flow and 18% of low flows. However, the largest relative impacts on low flow are seen in Northern Province where small areas of forestry are confined to humid upper catchments that are the principal source of dry-season flow in otherwise dry secondary catchments.

Introduction

South Africa is a relatively dry country and subject to recurring droughts which may last for several years. During a drought period in the 1920s there was concern and conflict over the possible impacts of the extensive planting of trees on the amount of water in rivers and streams. Some people believed that tree-planting would increase water supplies (for example Brown, 1877) but others argued that trees used more water than the vegetation they replaced. This concern resulted in the establishment of a South African hydrological research programme to determine the influence of plantations (Wicht, 1939). This research programme has shown that plantations do reduce the total annual runoff from catchments in proportion to the area planted and depending on tree type, with the extreme being the drying up of a fully afforested catchment (Nänni, 1970; Van Lill et al., 1980; Bosch and Hewlett, 1982; Van Wyk, 1987; Scott and Smith, 1997). This research programme has also shown that the reduction in low (dry-season) runoff is somewhat greater than for total annual runoff (Smith and Scott, 1992a; Scott and Smith, 1997).

On the basis of the early research results and other considerations, a State President's Water Matters Committee (1970) recommended the regulation of afforestation in South Africa. This led to the Forest Amendment Act no. 40 of 1972 that established the Afforestation Permit System (APS). This system was designed to ensure that forestry (post-1972) used no more than a pre-determined percentage of the water in a catchment by requiring land-owners to obtain permits to establish new plantations (Van der Zel, 1995).

The impacts of plantations on streamflow were estimated for the APS using a modification of a simple but robust model of plantation water use developed by Nänni (1970). Nänni's curves were based on hydrological studies of grassland and pine-afforested catchments at Cathedral Peak in the KwaZulu-Natal Drakensberg. Modifications that incorporated the results of other hydrological studies in the USA and elsewhere, produced the curves that were applied in the APS (Van der Zel, 1990; 1995). These "Van der Zel curves" predicted the effects of two different rotation lengths of forestry (15 and 40 years) but did not account for differences between species or site conditions (Bosch and Von Gadow, 1990). The curves were also adapted to account for the effects of forestry in the Pitman models used to estimate water resources in South Africa (HRU, 1981; DWA, 1986; Midgley et al., 1994).

Earlier estimates

While the results of the hydrological research were very clear, there was a lack of information about the impacts of plantations on water resources in the country as a whole. The first robust estimate of the impacts of plantations at a national scale was based on the forestry impact curves and catchment mean annual runoff (MAR) calculated in the HRU (1981) study. Plantations were estimated to be using an additional 1 284 x 10^6 m^3/yr of water in 1980, about 7.9% of the usable portion of total water resources (DWA, 1986). Given a total plantation area of 1.13 x 10^6 ha

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(DWA, 1986), the mean incremental water use of plantations is equivalent to 1 136 m^3/ha·yr or an average reduction in annual runoff from afforested land of 113.6 mm.

A new approach

As the demand for water by all sectors of the economy has increased, decision-makers at national and regional levels have required better information on which to base their decisions. A detailed picture of the impacts of plantations on water resources at the national and regional scale was needed. The Department of Water Affairs and Forestry (DWAF) commissioned the CSIR's Division of Water, Environment and Forestry Technology to produce an easy-to-use yet comprehensive reference manual which would provide information on the extent and distribution of forestry within the catchment system and magisterial districts of South Africa, and estimate the impacts of afforestation on streamflow (water yield) within each geographical unit. The resultant manual (Le Maitre et al., 1997) was designed to provide a balanced and scientifically sound estimate of the effects of forestry on both the mean annual streamflow (runoff) and mean annual low flow from each class of catchment (primary, secondary, tertiary and quaternary), magisterial district or province. In addition to the manual, which is a book of tables, the results of this study have been included in a PC-based spatial decision support system, CIMS (catchment impact modelling system). This *ArcView3* package allows the user to simulate the effects of further afforestation, or deforestation, on water yield from a particular quaternary catchment.

This paper describes the methodology, the sources of information and the assumptions and reasoning behind the modelling that produced the above products, and describes how all inputs were integrated by means of a geographical information system (GIS) to produce the final estimates. We present some summary and sample results from the exercise, and discuss some of the more striking findings arising from the analysis.

Methods and sources of data

The project involved using a GIS to integrate numerous types of information on a spatial basis, and separate out 72 000 individual geographical units with homogeneous characteristics in terms of tree genus planted, forestry suitability and streamflow (Fig. 1). The effects of forestry were modelled at the level of these units, and the results aggregated at several levels of catchment and administrative units to produce the requisite tables or database. The Arc/Info GIS software (ESRI, 1997), spreadsheets, database software and statistical analysis software were used for the calculations and to summarise the data. The spatial data sets that were combined were:

- those needed to define the geographical location (namely, magisterial district and provincial boundaries, quaternary and higher level catchment boundaries);
- the forestry economic zones (DoF, 1984) which were used to link the statistics on the forestry rotation lengths (DWAF, 1996) to sets of magisterial districts;
- the area of forestry by tree type and growth potential; and
- rainfall, from which virgin runoff was derived, and monthly runoff for each quaternary catchment from which virgin annual low flow was calculated.

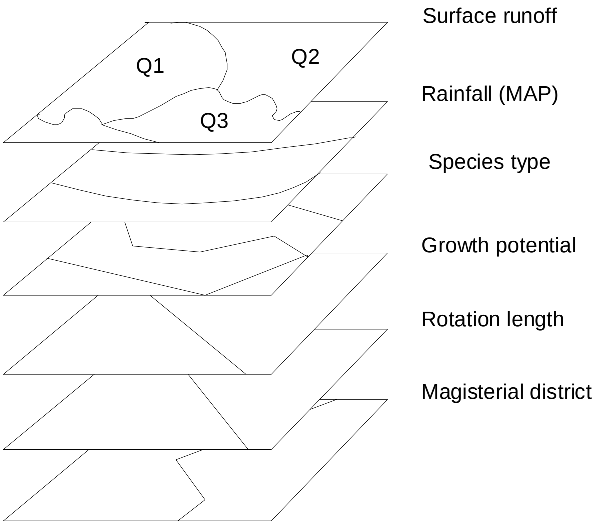


Figure 1
Schematic representation of the various spatial data layers that were combined by means of the Arc/Info geographical information system to delineate uniform blocks of forestry, derive the necessary input data to model the effects of forestry on streamflow and summarise these at the quaternary catchment or magisterial district level

Calculating the reductions in streamflow due to afforestation

Flow reduction models

Flow reductions were calculated using the empirical models developed by Scott and Smith (1997). These are slightly modified from those presented by Smith and Scott (1992b) and were applied using an algorithm similar to that given by Scott and Le Maitre (1993). The models are derived from the results of four long-term catchment experiments at:

- Westfalia near Tzaneen in Northern Province
- Mokobulaan, Mpumalanga Province escarpment (two experiments)
- Cathedral Peak, KwaZulu-Natal Drakensberg
- Jonkershoek near Stellenbosch in the Western Cape Province.

These catchments were planted with *Eucalyptus grandis* or *Pinus patula* except for those in the Western Cape which were planted with *P. radiata*. The curves shown in Figs. 2a and 2b predict the percentage reduction in the virgin total or low flow (i.e. the runoff under the natural grassland or fynbos vegetation) as a function of stand age for eucalypt and pine stands in both so-called "optimal" and "sub-optimal" growth zones.

Data required to apply the models

Scott and Smith (1997) provide a suite of eight curves and the following information is needed to select a specific curve and apply it:

- Is the plantation type pine or eucalypt, or if something else (e.g. wattle or poplar), to which species group is it most

Figure 2a
The flow reduction curves for eucalypts modified from Scott and Smith (1997) to take account of riparian zones being left unplanted. For more information see the text.

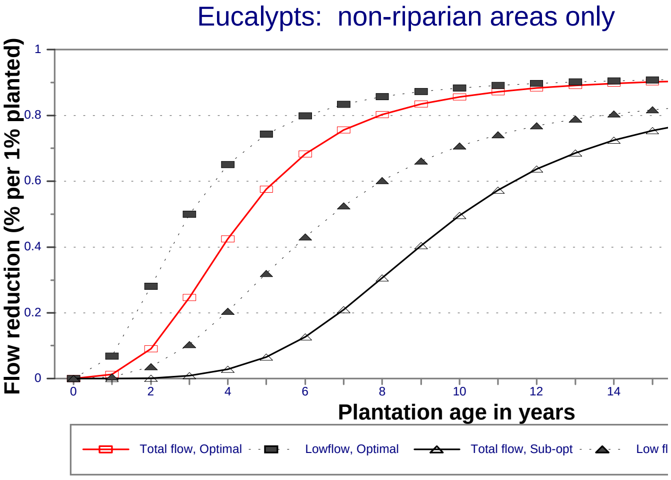
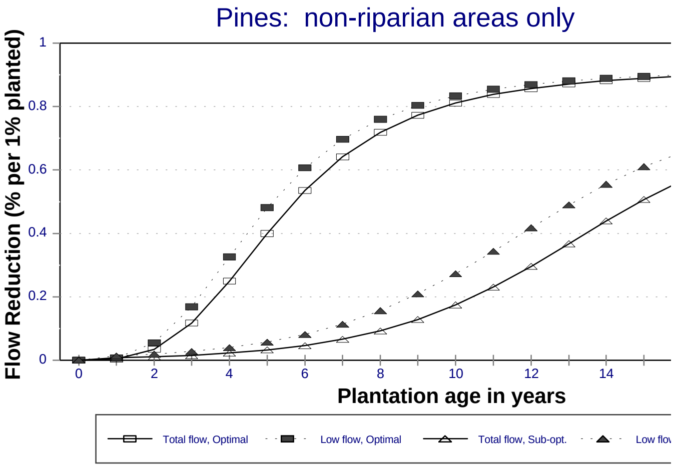


Figure 2b
The flow reduction curves for pines modified from Scott and Smith (1997) to take account of riparian zones being left unplanted. For more information see the text.



similar in its expected hydrological effects? (Select the pine or eucalypt curve).

- The mean annual rainfall and whether the plantation is in a high suitability growth zone for forestry or not? (Select the applicable long-lag or short-lag curve).
- Is a prediction of effects on total or low flow desired? (Select the total or low-flow model).
- As the models predict percentage flow reduction as a function of age, the forestry rotation length and age class distribution (area of each age class) need to be known.
- To relate the predicted reductions in flow (%) to an actual water resource, the virgin MAR or low flow for the planted area is needed; as is
- The specific area of plantation that shares the above common characteristics.

The data that were used and the assumptions that were made to arrive at estimates of the above model inputs are described in detail in the sections that follow.

Water use by trees planted in riparian zones

The models of Scott and Smith (1997) were adjusted to allow for the fact that riparian zones, in modern forestry practice, are left unplanted. This adjustment was necessary because the original flow-reduction models were developed from catchment experiments where trees were planted through the riparian zones, whereas research has shown that not planting riparian zones can lead to a greater saving in streamflow than would result from not planting the same area of an up-slope portion of the catchment (Scott and Lesch, 1995b).

The riparian adjustment was derived as follows. As a general guideline, riparian zones cover about 10% of a catchment. Based on experimental results, it can be estimated that clearing timber plantation in this riparian area will result in double the water yield gains that would result from clearing the same area of similar vegetation elsewhere in the catchment. The actual difference between riparian and non-riparian plantation may be as high as three times as much after experimental clearing (Scott and Lesch, 1995b), but riparian zones must carry some vegetation at all times, and will seldom have really short vegetation. Thus, the flow reduction curves were adjusted by the factor derived in Table 1.

Use of the adjusted flow-reduction curves assumes that all plantation forestry is non-riparian. Such a distribution of plantings is the ideal, and is the objective of the forest industry, but does not necessarily reflect the actual situation on the ground in all forestry operations.

However, there is another minor source of error that compensates, at the scale of the summaries in this analysis, for an underestimate in flow reduction caused by planted or invaded riparian zones. The area of commercial plantations derived from the satellite images (see below) will include these narrow and small unplanted areas within the blocks of plantation. Thus, the measured area of forestry is likely to be a slight overestimate.

TABLE 1
DERIVATION OF AN ADJUSTMENT FACTOR FOR CASES WHERE NO RIPARIAN LAND IS PLANTED. THE INITIAL ESTIMATE OF FLOW REDUCTION (SCOTT AND SMITH, 1997) IS ADJUSTED BY MULTIPLYING BY THE FACTOR DERIVED BELOW

Area units	Water yield units	Relative water yield	Adjustment factor
whole catchment = 10	11	100%	
riparian zone = 1	2	18.18%	
upslope (non-riparian) = 9	9	81.82%	0.909

TABLE 2
THE AREA OF THE PRIMARY PLANTATION TYPES (WATTLE, PINE AND EUCALYPTS) IN SOUTH AFRICA IN RELATION TO THE ANNUAL RAINFALL

Plantation type	Annual rainfall class (mm)	Area	
		(ha)	%
Wattle	<800	9 009	8.12
	800 - 1 000	94 999	85.58
	>1 000	6 995	6.30
Total Wattle		111 003	
Pine	<800	109 738	13.38
	800 - 1 000	434 820	53.04
	>1 000	275 337	33.58
Total Pine		819 895	
Eucalypt	<800	31 414	6.21
	800 - 1 000	338 529	66.93
	>1 000	135 842	26.85
Total Eucalypt		505 785	
All species	<800	150 161	10.45
	800 - 1 000	868 348	60.44
	>1 000	418 174	29.11
Total		1 436 684	

Deriving the inputs to the flow-reduction model for the whole country

Areas and types of forestry

The current extent of commercial forestry plantations was derived from the final classified images used for the National Forestry Coverage Map prepared for the DWAF by the CSIR (Thompson, 1995). This is considered to be the most comprehensive and consistent spatial database of commercial plantations in South Africa, having been mapped from satellite images mainly taken during 1993. The plantation areas were classified as follows by Thompson (1995):

- **Pine** - pine plantations including other conifers such as *Cedrus, Widdringtonia* and *Cupressus* species.
- **Eucalypt** - eucalypt, poplar, oak and other hardwood plantations.
- **Wattle** - commercial plantations of *Acacia mearnsii* with small areas of other *Acacia* species.

In the Thompson (1995) study, the minimum mapping unit was 25 ha so that patches of plantation or woodlot smaller than this were excluded. The mapped satellite data were checked in the field by the Chief Directorate of Forestry of the DWAF. Areas of non-commercial plantings, such as woodlots and wattle-invaded areas and plantings at power stations and mines on the highveld, were excluded. While these adjustments are legitimate for the purposes of the National Forestry Coverage Map, their effects on the estimates of streamflow cannot be accurately quantified at present without a re-analysis of the satellite imagery.

New plantations are not reliably identified on satellite imagery until canopy closure equals or exceeds approximately 60%; a level reached between ten months to three years for different species and sites (Thompson, 1995). Hence some of the youngest plantations may have been omitted from the forestry map. In particular the area of plantations in the North-Eastern Cape has expanded significantly since 1990. The area of forestry in this region was therefore updated using information supplied by North East Cape Forests in 1996. Indigenous forests were also mapped by Thompson (1995) but were excluded from this study.

The areas of the basic forestry types in South Africa are summarised in Table 2. These figures for plantation areas will also not necessarily be the same as those of other forestry databases for South Africa, namely the commercial timber resources assessment (DWAF, 1996) or the Water Resources of South Africa (WR90; Midgley et al., 1994), but the differences are minor. For example, DWAF (1996) gives the total plantation area as 1 428 630 ha while this study gives the total area as 1 438 992 ha, a difference of about 0.73%. The total WR90 afforested area (including some indigenous forests) is given as 1 445 888 ha, a difference of about 1.21% from this report.

Grouping species with similar water-use characteristics

The flow-reduction curves are only directly applicable to *Eucalyptus grandis, Pinus patula* and *Pinus radiata*. Several other species are used in commercial forestry so these needed to be grouped into one of the three major plantation types:

Eucalypts: The effects on streamflow of *E. grandis* were assumed to be representative of all eucalypt species planted in plantations at present. An analysis of some measurements of transpiration by poplars suggested that their annual water use was similar to pines (Scott and Le Maitre, 1993). Nevertheless, because all hardwoods (e.g. poplars and oaks) were grouped with eucalypts in the National Forestry Coverage Map (Thompson, 1995), the flow-reduction curves for eucalypts were used for all hardwoods except wattles. The inclusion of poplars and other species under eucalypts is unlikely to have a significant impact on the estimates because the areas planted with these species only amount to about 0.6% of the total afforested area (DWAF, 1996).

Pines: The flow-reduction models for pines were used for all softwood plantings.

Wattles: There are inadequate data on the effects of wattles on streamflow. The canopy structure of wattle and its observed physiological response to high evaporative demands and drought conditions prompted us to apply the flow-reduction curves for pines to wattle plantations until further studies can provide more conclusive data.

Allocating flow reduction curves to sites

Scott and Smith (1997; Figs. 2a and 2b) found that the measured flow reductions could be divided into two groups: those with a long lag before decreases became evident and those with a short lag. They hypothesised that the long lag was the result of the slower growth rates of trees in sub-optimal growth zones. The slower growth rate would cause a slower decrease in streamflow than is experienced in optimal growth zones.

However, the differences between the two pairs of pine curves are not, as hypothesised by Scott and Smith (1997), solely a function of growth zone optimality. Another important factor, water availability, is incorporated in the shape of the relative flow reduction curves. The long-lag curves fit data from the wettest pine sites (large virgin runoff) where it takes longer for trees to cause a large relative reduction in flow. The wettest experimental site (Cathedral Peak) had the lowest proportional flow reduction, and the driest pine catchment had the highest proportional reductions reached soonest in the rotation (Mokobulaan, with 100% reduction at 12 years). It follows, therefore, that the drier the site the sooner the same proportional reductions will be reached. Thus the short-lag curves are thought to be most appropriate for both the best sites, where initial growth is fast, and the drier sites where, because of a small water surplus, plantations have a large relative impact earlier in the rotation.

A classification of the optimality of forestry sites was derived from a recently completed study of the regional forestry potential for eucalypts and pines in South Africa (Fairbanks, 1995; Fairbanks and Smith, 1995). The forestry potential models use information on the soil depth and water-holding capacity and rainfall to estimate growth potential and the risks of mortality or reduced growth during droughts. In the absence of specific information, the suitability classification for pines was also applied to wattle plantations. Fairbanks and Smith (1995) identified five forestry potential classes which we have reduced to two: optimal (80 to 100% suitability for forestry) and sub-optimal (<80% suitability). Optimal was described as:

> "Soil moisture is seldom limiting. Annual rainfall at least 1 000 mm, with optimal temperatures combined with deep soils with a high water-holding capacity. Risk of tree mortality or reduced growth during drought conditions is very low. Sub-optimal conditions will be very localised."

The matching of the flow-reduction curves to forestry sites therefore used the following rules incorporating both site optimality and water availability:

- if the forestry potential was ≥ 80% then the short-lag curves (for so-called optimal zones) were used;
- if the forestry potential was < 80% then:
  - if the mean annual precipitation (MAP) was ≥ 1 000 mm then the long-lag curves (for so-called sub-optimal zones) were used;
  - if the MAP was < 1 000 mm then the short-lag curves were used.

Forestry economic zones

The DWAF developed the concept of "economic zones", based on regional differences in the species that were planted and the products the plantations are managed to supply, and summarises information on the industry by these zones. The boundaries of the 12 economic zones were based on those of the magisterial districts and provinces at the time (DoF, 1984). Some of these boundaries have been altered but the changes were small so this analysis used the original allocation of magisterial districts to economic zones.

Species composition, rotation lengths and product mix

Information on the mean forestry rotation lengths was obtained from the 1994/95 statistics for each forestry economic zone (DWAF, 1996). This report gives the area-weighted mean clear-felling age for different timber product types and species groups.

The data are tabulated for the following five species groups: softwoods (primarily pines but including other conifers), eucalypts (*Eucalyptus grandis* and other eucalypt species), wattles (primarily *Acacia mearnsii*), poplars and other hardwoods. The planted areas under each species group are also divided into the following product categories; sawlogs, poles and droppers, mining timber, pulpwood, matchwood, firewood and unspecified (including other products). The former Transkei was not included in any of the economic zones. As it is situated between the Eastern Cape and Southern Natal economic zones, the magisterial districts of the Transkei east and north of Umtata were grouped with the Southern Natal economic zone and the remainder with the Eastern Cape economic zone.

For each of the species groups and product categories an area-weighted mean clearfelling age was given, where available. Where no clearfelling age was given for a category in an economic zone, the age for the most similar category was used. Unspecified rotation periods occurred most frequently in the product categories firewood and other. The missing data will have little impact on the accuracy of the reduction estimates because these two categories comprise less than 2% of the total planted area. Some amendments were also supplied (Van der Zel, 1997), and these have been incorporated in the analysis.

Age class distribution

No data on the age structure of the areas planted with the different product groups were available at the catchment scale. We assumed therefore that there would be a roughly equal area in each age class (i.e. there would be a normal age distribution) at the scale of a magisterial district or quaternary catchment. This meant that the mean streamflow reduction over the period between planting and clearfelling (Scott and Le Maitre, 1993) was used in all the calculations. This is the equivalent of the integral of the flow reduction curve over the length of the rotation divided by the rotation length in years. The mean rotation length cannot be used because the relationship between the rotation length and the flow reduction is curvi-linear (Fig. 2).

Calculating the reduction factors for each economic zone

The first step in applying the flow reduction curves (Fig. 2) was to calculate the mean reduction factor for each plantation type

TABLE 3
FORESTRY PRODUCTS AND ASSOCIATED ROTATION LENGTHS FOR PINE PLANTATIONS IN THE EASTERN TRANSVAAL ECONOMIC ZONE (DWAF, 1996), AND THEIR CALCULATED STREAMFLOW REDUCTION FACTORS

Product category	Area (ha) and rotation length (years)	Mean reduction factor (%/1% afforested)			
		Short-lag		Long-lag	
		Total flow	Low flow	Total flow	Low flow
Sawlogs	150 344 / 24	0.71	0.73	0.36	0.41
Poles and droppers	4 / 20	0.66	0.69	0.28	0.34
Mining timber	0 / 0	0.00	0.00	0.00	0.00
Pulpwood	23 444 / 18	0.63	0.66	0.24	0.30
Matchwood	0 / 0	0.00	0.00	0.00	0.00
Firewood	0 / 0	0.00	0.00	0.00	0.00
Other purposes	254 / 30	0.75	0.77	0.44	0.48
Area weighted mean reduction factor		0.70	0.72	0.34	0.40

(eucalypt, pine or wattle; see above) and rotation length as determined by the combination of product categories in each forestry economic zone. The area planted with each product group in each forestry economic zone differed, so an area-weighted mean reduction factor for each species group was calculated as follows:

(i) the reduction factor for each rotation, determined by tree type and product category, was multiplied by the corresponding area (planted or unplanted);
(ii) the results of step (i) were summed for all the product groups for a tree type; and
(iii) the resulting total was divided by the total area planted with that tree type in that specific economic zone.

The pine plantations (including all conifers) of the Eastern Transvaal economic zone can be used as a simplified example. The total planted area is some 174 000 ha, mostly sawlog plantations (Table 3). The mean reduction factors for annual total and low flows, in both sub-optimal and optimal zones, were calculated from the rotation lengths for each product group. The reduction factors were multiplied (weighted) by the respective areas and divided by the total area to give the final reduction factors used for pines in the Eastern Transvaal economic zone. Thus a reduction factor of 0.70 was derived to calculate the total flow reductions for all pine plantations to which the short-lag curve was applicable in the Eastern Transvaal economic zone.

Streamflow data

Estimates were to be made of the effects of afforestation on both total flow and low flow. As a starting point we therefore needed a baseline of virgin runoff and low flow from each block of afforested land.

Estimating runoff from the rainfall in forestry areas

The rainfall, and hence water yield, can vary quite markedly from place to place even within a quaternary catchment, especially in the montane areas where many plantations are situated. We had expected that plantation areas, which are typically located in the high-rainfall, montane areas, would tend to have a higher rainfall than the mean for the entire catchment, and hence also a higher virgin runoff. We therefore estimated virgin MAR for afforested blocks of land based on the best estimate of annual rainfall.

The basis of our estimates was the MAP data layer, with 100 mm isohyets, obtained from the WR90 project (Midgley et al., 1994) on compact disc (CD-ROM). These rainfall data were used to calculate the area-weighted mean rainfall for each plantation patch (polygon) in the data set. A hypothetical example is given below:

> A plantation polygon straddles two rainfall classes: 1 250 ha with 900 mm of rainfall and 2 450 ha with 800 mm of rainfall. The area-weighted mean rainfall is thus:
> (1250*900+2450*800)/(1250+2450) = 833.8 mm.

We chose to use the WR90 data in preference to the gridded rainfall data available from the Computing Centre for Water Research (CCWR) because the WR90 rainfall surface was from the same analysis that produced the MAR data. An analysis of the MAP data showed that, contrary to our preconceptions, the quaternary catchment and the plantation MAP did not differ greatly in general (Table 4). The mean catchment MAP was actually 36 mm greater than the mean plantation MAP and the median difference was 24.2 mm. More than 90% of the differences were less than 150 mm. There were some extreme differences (> 500 mm) but these were confined to small areas with very steep orographic rainfall gradients, for example the mountain areas in the Stellenbosch and Paarl districts.

MAP figures for each forestry polygon were converted to MAR (mm) using a set of generalised rainfall-runoff relationships provided by Pitman (1996) and used in the WR90 project (Midgley et al., 1994):

$$\text{MAR} = (\text{MAP-B+3}) + \frac{\text{C}}{\exp\left(\frac{\text{MAP-A}}{\text{C}}\right)}$$

where:
MAP = mm
exp = e to the power of
A = 75 + 45***Z***
B = 225 + 135***Z***
C = 150 + 90***Z***
Z = climate-related zone number, ranging from 1 to 9.

In general, the zone ***(Z)*** number is related to the rainfall, ranging from the driest (1) to the wettest (9) catchments. The above MAR formula also can only be used for a limited range of MAP values. For example the formula with a curve number of 9 is valid only for an MAP $\geq$ 550 mm and a curve number of 1 is valid only for MAP $\geq$ 300 mm.

Catchment (mean annual) low flow

The source data for the low flows was the monthly flow data sets for each quaternary catchment in South Africa developed in the WR90 project (Midgley et al., 1994). For each quaternary catchment a period of 70 years of real and/or synthesised virgin monthly flow data are available on the CD from the Water Research Commission (WRC), or directly from the CCWR. The data sets at the CCWR are updated with corrections and omissions as they become available.

TABLE 4
A COMPARISON OF THE MEAN ANNUAL RAINFALL (MAP) OF QUATERNARY CATCHMENTS IN WHICH FORESTRY OCCURS (MIDGLEY ET AL., 1994) AND THE MEAN ANNUAL RAINFALL OF AFFORESTED AREAS, AS DETERMINED BY OVERLAYING FORESTRY AND RAINFALL MAPS, SHOWING THE PERCENTAGE OF THE TOTAL AFFORESTED AREA IN EACH CLASS. FOR MORE INFORMATION SEE THE TEXT.

Quaternary catchment MAP (mm)	MAP of forestry plantations (mm)					
	<800	800 - 900	900 - 1 000	1 000 - 1 100	>1 100	Total
<800	7.82	5.31	0.64	0.36	0.00	14.17
800-900	2.42	26.11	2.13	1.25	0.24	32.16
900-1 000	0.19	17.36	3.91	6.09	0.89	29.31
1 000-1 100	0.02	2.74	0.56	5.67	0.03	9.74
>1 100	0.00	1.11	0.58	14.27	0.26	16.23
Total	10.45	52.61	7.83	27.64	1.47	100.00

Low flows were defined as those below the 75th percentile exceedance level (PEL). All the monthly flow volumes were sorted in descending order, then ranked from 0 to 100%. The cutoff value is the one closest to the 75% ranking (i.e. the 75th PEL) or the flow level exceeded in 75% of months. A 75th PEL has the conceptual advantage of returning on average the driest three months in a year. In effect this method involves using the lowest 25% of monthly flow volumes in the 70 year record (210 months out of 840), regardless of the years in which they occurred, the specific sequence in which they occurred, or the time of year.

The mean annual low flow (MALf) for each quaternary catchment was defined as one-seventieth of the sum of the volumes of the 210 low-flow months (the average amount of flow that one can expect during a three-month dry season), or in mathematical form:

$$\text{MALf} = \frac{1}{70}\sum_{1}^{210} Vol.$$

where:
Vol. = the monthly flow volume for each of the 210 months with flow volumes below the 75th PEL.

The MALf volumes were m^3 and were converted to millimetres depth using the quaternary catchment area. All blocks of land within a quaternary catchment were therefore assumed to have the same virgin low flow, which is different from the approach used to estimate the MAR of afforested land.

Cadastral boundaries: magisterial, provincial and catchment

The boundaries of the magisterial districts and provinces were taken from the national district delineation map supplied by the Human Sciences Research Council (HSRC), as updated and corrected by the CSIR's Division of Building Science and Technology in November 1995. It was the best available map of the internal legislative-administrative boundaries at the time. The catchment boundaries were those used in the WR90 study (obtained from Steffen, Robertson and Kirsten Inc.) These are, at present, the definitive catchment boundaries used by the DWAF and the various water boards in the country to conduct water-use planning. The outer boundaries of the catchment spatial data layer (coast and RSA borders) were used to define the outer boundaries of the country. Where the boundaries of the magisterial district data layer did not coincide they were clipped or adjusted to conform to the catchment data layer boundaries.

Results

The statistics of the effects of forestry on streamflow have been summarised using two different spatial units:

- The first summary is hydrological and based on the spatial unit of the quaternary catchment, which is the smallest practical unit for catchment management at a regional scale and is a fundamental planning unit used by the DWAF.
- The second summary is based on magisterial districts because they are the basic administrative and political units. The magisterial districts are grouped into the nine different provinces with a final summary for the whole country.

The extent of commercial forestry and its estimated effect on water resources at the primary and secondary catchment level in South Africa are presented in Table 5 and an extract of a summary by quaternary catchment is given as Table 6. A summary of the same data is presented by province in Table 7, and an extract of a summary by magisterial district is given as Table 8. These tables present just some of the summaries possible from the large database.

Commercial plantations cover only 1.18% of the surface of South Africa, and on an area basis constitute a minor land use. But as plantations occur in the high rainfall regions of South Africa they have an incremental water use equivalent to 3.12% of the total runoff of South Africa and, more significantly perhaps, are estimated to reduce mean low flows by 7.78%. The reason for the impacts being disproportionate to the area under forestry can be shown with the following statistics. The total area of quaternary catchments which contain plantations is only 14.2% of the total land area but these catchments receive 22.2% of the rainfall (by volume) and produce 38.9% of the MAR and 54.8% of the MALf.

At the primary catchment scale, the greatest impacts are on the river systems draining the Drakensberg escarpment in Mpumalanga (catchment X) where the annual runoff has been

TABLE 5
THE AREA OF COMMERCIAL PLANTATIONS IN EACH PRIMARY CATCHMENT AND THE REDUCTION IN MAR (PERCENTAGE OF TOTAL AND LOW FLOW) ATTRIBUTED TO PLANTATIONS. THE IMPACTS OF FORESTRY IN SWAZILAND HAVE BEEN EXCLUDED AND CATCHMENTS AFFECTED BY THIS ARE INDICATED BY AN ASTERISK (*) IN THE TABLE (ADAPTED FROM LE MAITRE ET AL., 1997)

Primary catchment	River system	Catchment area (ha)	Mean annual (mm)			Plantation area (ha)	Runoff reduction (%)	
			Precipitation	Total flow	Low flow		Total flow	Low flow
A	Limpopo	10 873 287	528	22	0.783	20 994	0.886	1.817
B	Olifants	7 350 308	625	40	1.576	88 055	3.712	11.228
C	Vaal	19 628 409	525	23	0.298	1 666	0.013	0.014
D	Orange	37 824 180	254	7	0.085	957	0.015	0.009
E	Olifants (W Cape)	4 906 252	213	21	0.078	1 000	0.152	0.205
F	Namaqualand	2 850 622	128	1	0.000	0	0.000	0.000
G	W Cape coast	2 524 374	477	81	0.877	16 442	1.732	3.205
H	Breede & SW Cape coast	1 551 872	544	135	1.916	5 031	0.428	1.159
J	Gouritz	4 513 434	260	15	0.107	184	0.030	0.012
K	S Cape coast	716 825	756	181	9.659	75 616	9.446	12.327
L	Gamtoos	3 473 106	283	14	0.166	9 027	1.373	1.681
M	Port Elizabeth region	261 157	555	57	0.508	6 055	2.746	2.816
N	Sundays	2 122 532	330	13	0.025	0	0.000	0.000
P	E Cape coast	530 807	561	33	0.123	628	0.080	0.251
Q	Gt Fish	3 022 811	410	17	0.162	7 640	0.549	1.875
R	Border coast	791 831	675	73	1.306	14 891	1.359	2.869
S	Great Kei	2 048 308	610	51	1.386	23 385	1.600	2.762
T	Transkei region	4 648 239	857	158	4.908	203 045	2.813	3.367
U	S KwaZulu-Natal	1 829 157	928	171	6.898	199 994	4.848	5.810
V	Tugela	2 902 399	824	137	3.126	22 628	0.392	0.468
W*	N KwaZulu-Natal & Mpumalanga highveld	4 507 461	825	105	4.133	403 150	5.929	8.820
X*	Mpumalanga escarpment	2 857 158	769	100	6.901	336 294	14.801	22.383
South Africa		121 734 527	448	37	1.069	1 436 684	3.162	7.795

reduced by 14.8% and the low flows by 22.4%, followed by the coastal catchments of the George-Humansdorp region (catchment K) with reductions of 9.4% and 12.3% in annual and low flow respectively. Where forestry is confined to a humid 'island' within a dry region, the greatest impacts on low flow relative to annual flow are apparent. An extreme example is the Olifants and Letaba River systems (primary catchment B) where the reduction in low flows is 11.2% compared with the total flow reduction of 3.7%. This is a ratio (low/total) of about 3.0 compared with a ratio of around 1.5 for the wetter primary catchment X and 2.5 for the whole country. Differences of this sort are particularly marked in the Letaba River system (secondary catchment B8). Here afforestation of only 3.6% of the land area results in a reduction of 8.8% in the total flow and 28.1% in the low flow, a ratio of low/total of 3.2.

Mpumalanga Province with the largest area (575 882 ha) and greatest density of commercial plantations (7.24% of the province) experiences the largest flow reductions followed by KwaZulu-Natal, Northern Province, Eastern Cape and Western Cape where the total streamflow is reduced by between 2 and 3%. It is notable that KwaZulu-Natal, with a high proportion of forestry, and Northern Province, with a small proportion of forestry, experience similar reductions in surface runoff. This is a reflection of the more even distribution of water-yielding zones in the KwaZulu-Natal Province.

Sensitivity to allocation of the long or short-lag flow reduction curves

The effect on the results of different assignments of the curves for so-called optimal or sub-optimal growth zones was tested as follows:

(i) **Scenario 1: Curves applied simply according to forestry potential** (<80% potential = long lag curves; >80% potential = short lag curves). This is expected to underestimate the impact of forestry, because of the combination of short rotations with the long-lag curves, especially on sites with a low water availability. To apply the so-called sub-optimal curves for pine to most of the lower-rainfall sites for pine and wattle involves extrapolating from the wet extreme to the dry, and can be expected to introduce large errors.

(ii) **Scenario 2: Apply the so-called optimal growth zone curves throughout**. All areas were modelled using the short-lag curves; this approach is expected to produce a somewhat conservative estimate of water-use by plantations.

Under Scenario 1 the mean total flow reductions would be 69.7 mm (3.2%), which is 29% lower than our estimate. Under Scenario 2 the mean reduction in total flow would increase

TABLE 6
EXTRACT FROM A SUMMARY TABLE AT THE LEVEL OF SECONDARY CATCHMENTS, SHOWING THE AREA OF COMMERCIAL PLANTATIONS (BASED ON THOMPSON, 1995), AND THE REDUCTION IN MAR AND LOW FLOW ATTRIBUTED TO PLANTATIONS. SECONDARY AND PRIMARY CATCHMENTS WITHOUT ANY PLANTATIONS HAVE BEEN EXCLUDED TO KEEP THE TABLE AS SHORT AS POSSIBLE. CATCHMENT AREAS FALLING IN SWAZILAND HAVE BEEN EXCLUDED FROM THE ANALYSIS. THE AFFECTED CATCHMENTS ARE INDICATED BY AN ASTERISK (*) IN THE TABLE (ADAPTED FROM LE MAITRE ET AL., 1997)

Catchment name	River system	Catchment area (ha)	Mean annual (mm)			Plantation area (ha)	Total run-off reduction (%)	Low flow reduction (%)
			Precipitation	Total flow	Low flow			
A	Limpopo	10 873 287	528	22	0.783	20 994	0.886	1.817
V1	Upper Tugela	762 738	885	211	3.979	2 957	0.158	0.162
V2	Mooi	286 797	800	140	4.059	8 420	1.421	1.328
V3	Buffalo	980 199	802	104	2.066	3 305	0.247	0.271
V4	Middle Tugela	175 359	817	97	2.813	1 726	0.554	0.561
V5	Lower Tugela	134 812	878	116	5.782	3 373	1.028	0.953
V6	Klip	371 048	757	84	2.036	470	0.097	0.086
V7	Boesmans	191 446	825	163	4.291	2 376	0.639	0.698
V	Tugela	2 902 399	824	137	3.126	22 628	0.392	0.468
W1	Mhlatuzi	564 673	1011	164	7.235	63 547	4.657	7.703
W2	Mfolozi	1 000 621	803	97	2.754	43 485	2.949	6.133
W3	Mkuzi	952 955	769	56	2.254	39 165	4.285	4.323
W4*	Pongola & Ngwavuma	919 763	774	125	5.066	47 967	4.044	5.555
W5*	Great Usutu	808 491	861	129	4.962	193 133	13.097	19.400
W7	Maputaland coast	258 226	769	43	3.740	15 853	3.023	3.028
W*	N KwaZulu-Natal & Mpumalanga highveld	4 507 461	825	105	4.133	403 150	5.929	8.820
X1*	Komati	861 824	811	102	7.269	79 649	9.001	13.219
X2*	Crocodile	1 044 541	816	118	8.405	177 455	16.823	21.272
X3	Sabie & Sand	631 016	753	116	7.404	79 190	18.865	36.758
X*	Mpumalanga escarpment	2 857 158	769	100	6.901	336 294	14.801	22.383
South Africa		121 734 527	448	37	1.069	1 436 684	3.162	7.795

relative to our estimate by 6.5% to 105 mm (3.34%) and increase to 8.1% of low flows.

Under our allocation of the curves, the range in total flow reductions for pine plantations is from 106 mm (32%) - on high rainfall sites with a forestry potential of <80% (sub-optimal) - to 151 mm (56%) on high rainfall sites with good growth potential (optimal). For wattles, which typically grow on drier forestry sites on short rotations (Table 2), the reductions are far lower, ranging from 11 to 52 mm (6 to 41%) for sub-optimal to optimal sites respectively. For eucalypts the equivalent range was 44 to 92 mm (16 to 42%). The area-weighted mean reductions for wattles, pines and eucalypts are 50, 120 and 75 mm/yr respectively.

Discussion

This is the first study to estimate the impacts of plantations on low flows at a national and regional scale. The previous analysis of the impacts of plantations estimated that the volume of runoff used by 1.13 x 10^6 ha of plantations was about 1 284 x 10^6 m^3/yr (DWA, 1986) or 113.6 mm in rainfall equivalents. The analysis reported here gives an estimate of 1 417 x 10^6 m^3/yr, about 10% more than the value given by DWA (1986). However, the total area under plantations has increased by about 27% and the reduction per unit plantation area is lower, being 98.7 mm compared with the 113.6 mm from DWA (1986). Using the Van der Zel (1995) curves - in the form of the equations given by Midgley et al. (1994) - and assuming that all plantations are either on 15 or 40 year rotations, the range in total flow reductions, given the current areas of forestry, is from 95 mm to 249 mm for 15 and 40 year rotations, respectively, or 2.87 to 7.49% of the total annual runoff (1 368 to 3 573 x 10^6 m^3/yr). Thus our best estimate of 3.16% is slightly higher than that from the Van der Zel curve for 15 year rotations but less than half of that estimated for the highly improbable situation where all plantations are on 40 year rotations.

The new estimates of forestry's effects on surface runoff given in this paper are more accurate than previous ones as they are the first to incorporate:

- the significant differences in the patterns of flow reductions over time caused by the two dominant species groups of eucalypts and pines;
- rotation lengths which are close to those used in practice, at least at the scale of economic zones;
- water availability at the afforested sites, based on the estimate of the annual rainfall in the plantation areas; and
- an allowance for water savings caused by not planting riparian zones within plantations.

TABLE 7
SUMMARY TABLE BY PROVINCE OF THE AREA OF COMMERCIAL PLANTATIONS AND THE REDUCTION IN MEAN TOTAL RUNOFF AND LOW FLOW (PERCENTAGE OF VIRGIN) ATTRIBUTED TO PLANTATIONS IN EACH PROVINCE. THE NORTH WEST AND NORTHERN CAPE PROVINCES HAVE NO AREAS UNDER COMMERCIAL PLANTATIONS (FROM LE MAITRE ET AL., 1997)

Province	Area (ha)	Mean annual (mm)			Plantation area		Runoff reduction (%)	
		precipitation	total flow	low flow	(ha)	(%)	total flow	low flow
Eastern Cape	16 974 730	552	61	1.675	232 288	1.368	2.312	3.583
Free State	12 993 572	532	27	0.265	2 413	0.019	0.026	0.031
Gauteng	1 651 904	670	33	2.134	17	0.001	0.001	0.001
KwaZulu-Natal	9 212 465	844	131	4.324	468 208	5.082	2.826	4.469
Mpumalanga	7 957 055	730	79	4.001	575 882	7.237	9.867	18.150
North West	11 601 009	451	9	0.193	0	0.000	0.000	0.000
Northern Cape	36 198 066	202	3	0.000	0	0.000	0.000	0.000
Northern Province	12 214 309	534	28	0.864	78 169	0.640	2.477	8.980
Western Cape	12 931 417	346	51	0.796	79 706	0.616	1.959	6.024
South Africa	121 734 527	448	37	1.069	1 436 684	1.180	3.162	7.795

TABLE 8
EXTRACT FROM A SUMMARY TABLE AT THE MAGISTERIAL DISTRICT LEVEL SHOWING THE AREA OF COMMERCIAL PLANTATIONS (PERCENTAGE OF MAGISTERIAL DISTRICT) AND THE REDUCTION IN MAR AND LOW FLOW ATTRIBUTED TO PLANTATIONS. A VALUE OF 0 INDICATES THAT THE PERCENTAGE OF THE DISTRICT UNDER PLANTATIONS, OR THE IMPACT ON RUNOFF IS TOO SMALL TO BE SHOWN WITH THE GIVEN NUMBER OF DECIMAL PLACES (ADAPTED FROM LE MAITRE ET AL., 1997)

Province	Magisterial district	Area (ha)	Mean annual (mm)			Plantation area (%)	Total flow reduction (%)	Low flow reduction (%)
			precipitation	total flow	low flow			
Western Cape	Mossel Bay	187 723	485	70	1.797	2.072	4.524	7.09433
Western Cape	Parl.	108 803	1 066	522	6.373	4.871	2.457	4.39047
Western Cape	Piketberg	453 764	371	43	0.201	0.046	0.073	0.07972
Western Cape	Riversdale	390 816	445	47	1.288	0.610	2.064	3.93392
Western Cape	Simons Town	24 288	688	135	0.919	0.005	0.007	0.00383
Western Cape	Somerset West	23 218	896	359	6.411	4.666	4.632	4.01544
Western Cape	Stellenbosch	42 596	871	299	4.135	2.106	1.695	2.05522
Western Cape	Strand	12 451	985	444	9.173	4.635	2.173	3.05863
Western Cape	Swellendam	404 699	382	50	1.448	0.148	0.826	1.02283
Western Cape	Tulbagh	93 579	639	211	1.440	3.027	1.132	2.36415
Western Cape	Uniondale	304 471	489	35	0.969	0.022	0.034	0.04245
Western Cape	Wellington	46 083	645	201	1.942	0.313	0.301	0.11009
Western Cape	Worcester	405 768	546	158	1.314	0.003	0.004	0.00434
Western Cape	Wynberg	30 746	741	171	1.032	3.623	5.126	2.76474
Western Cape		12 931 417	346	51	0.796	0.616	1.962	6.03318

The inclusion of these refinements gives us confidence that the new estimates are an important advance. Nevertheless, we believe that it is important to bear in mind the limitations discussed below when interpreting these results.

Sources of error in estimating flow reductions

Although the streamflow reduction models used in this analysis are the most appropriate for a study of this scale and represent an improvement over other methods previously available, there are shortcomings in the modelling. In this section these shortcomings and sources of error derived from the key assumptions that were made are listed and explained.

Extrapolating the models

The models 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 constitutes extrapola-

TABLE 9
AN ANALYSIS OF THE SENSITIVITY OF THE MODELLING RESULTS TO DIFFERENT ALLOCATIONS OF THE FLOW REDUCTION CURVES TO PLANTATION AREAS (PLANTATION AREA AND ROTATION LENGTHS ARE FIXED)

Species group	Forestry potential	Rainfall class mm	Reduction model	Applicable plantation area (ha)	Reduction in total flow (mm)	Reduction in low flow (mm)
Using current rules: recommended						
Wattle	<80%	<1 000	Short-lag	74 592	50.37	2.3383
Wattle	<80%	>1 000	Long-lag	2 460	11.75	0.5790
Wattle	≥80%	all	Short-lag	33 952	51.67	2.3780
Pine	<80%	<1 000	Short-lag	434 363	98.11	5.6533
Pine	<80%	>1 000	Long-lag	57 671	106.65	5.8568
Pine	≥80%	all	Short-lag	327 862	151.22	12.1334
Eucalypt	<80%	<1 000	Short-lag	285 278	64.70	4.4699
Eucalypt	<80%	>1 000	Long-lag	20 075	44.15	7.3779
Eucalypt	≥80%	all	Short-lag	200 432	92.26	8.4570
Total				1 436 684	98.65	7.06
Scenario 1: If forestry potential ≥80% then use short-lag curve, otherwise use long-lag curve						
Wattle	<80%	all	Long-lag	77 051	6.79	0.4528
Wattle	≥80%	all	Short-lag	33 952	51.67	2.3780
Pine	<80%	all	Long-lag	492 034	47.82	3.1549
Pine	≥80%	all	Short-lag	327 862	151.22	12.1334
Eucalypt	<80%	all	Long-lag	303 353	20.28	2.6556
Eucalypt	≥80%	all	Short-lag	200 432	92.26	8.4570
Total				1 436 684	69.72	5.68
Scenario 2: Use the short-lag curves for all commercial plantations						
Wattle	all	all	Short-lag	111 003	51.82	2.3706
Pine	all	all	Short-lag	819 895	128.11	8.6181
Eucalypt	all	all	Short-lag	505 785	78.51	6.4114
Total				1 436 684	104.76	7.36

tion, and introduces some uncertainty. Most significantly, the experimental catchments have a mean annual precipitation (MAP) range of 1 150 to 1 600 mm which is significantly wetter than most forestry areas in South Africa (Table 2). On the other hand, the models fit pooled data from well-maintained catchment experiments involving the primary tree species in South African forestry, spread over a wide geographic range (Scott and Smith, 1997). For example, the long-lag model for pines was based on two catchments (in the Drakensberg and the Western Cape) and was verified against an independent catchment in the Drakensberg (Scott and Lesch, 1995a); similarly the short-lag model for eucalypts (in optimal growth zones) was fitted to data from two catchments with MAPs of 1 150 mm and 1 600 mm.

The model results are sensitive to the allocation of the long or short-lag curves to different blocks of forestry. This is a crucial element of the whole modelling exercise. Our solution is an approximation at this stage based on our best judgement as forest hydrologists, but further work either to develop broader scientific criteria for the allocation of curves to sites or to develop a family of curves that are more site-specific, would be advisable.

There are variables which cannot be addressed by the models because the models were derived from specific sites. For instance, the streamflow reductions may be smaller in catchments where the soil profiles are shallower, allowing less rain to be stored in the catchment for later use by the trees. The streamflow reductions also may be higher in mist-belt catchments where much of the rain is in the form of long-duration, low-intensity storms which could lead to greater rainfall interception losses from tree canopies.

Limitations of the original experimental data - Synthesised models

Of the eight flow-reduction curves used in this study (Fig. 2), six are based on actual research results, namely the long-lag curves for pines (sub-optimal growth zones) and the short-lag curves for eucalypts and pines (optimal). Due to the lack of experimental data the remaining two long-lag curves for eucalypts were synthesised from the original models and lie within the extremes described by them (Fig. 2a, sub-optimal zones). These streamflow reduction models for eucalypts were synthesised by adjusting the short-lag curves for eucalypts by the relationship between the two pairs of pines curves (Scott and Smith, 1997). While we feel these synthesised models give improved estimates of the effect of afforestation on streamflow, they are based on best judgement and not real data. It would be advisable to improve the underlying models once better information is available. In the event, under the allocation rules described above, these models were applied to only 4% of eucalypt plantings.

Use of the appropriate rotation length

The models are applied by integrating the flow reductions following forestry over the rotation length. The model for pines in sub-optimal growth zones is particularly sensitive to the rotation length because of the long lag before large flow reductions occur (Scott and Smith, 1997). In modelling the effects of forestry an inappropriate combination of short rotations with the long-lag models (sub-optimal growth zones) will lead to serious under-estimates of the reductions in streamflow. Even the use of a mean rotation length where a wide range of actual rotation lengths occurs will lead to under-estimates of streamflow reduction. However, more detailed data on rotation lengths than those used here are not available at present.

Silvicultural improvements: Thinning, site preparation, fertilisation and tree-breeding

The models were developed from experiments in which the plantations received what were then the standard silvicultural treatments for sawlog production. New silvicultural treatments aimed at improving the growth rates of trees, for example site preparation and fertilisation, may also increase their water use, with the result that the flow reduction models - of Scott and Smith (1997) - would underestimate streamflow reductions under current silvicultural practices. For similar reasons, second rotation crops that dominate a site more quickly than a first rotation crop, for reasons of reduced competition, might have an earlier impact on streamflow than is predicted by the models. Research has indicated that unthinned plantations may have a slightly greater effect on streamflow than predicted by the models (Van der Zel, 1970; Lesch and Scott, 1997).

Conclusions

For the first time in South Africa, the effects of afforestation on streamflow have been estimated, based on the tree type and growth zone, and distributed according to quaternary catchment and magisterial district. This information ought to be useful to regional and national planners.

In roughly 12 years since the last national assessment, the area of commercial forestry has grown by 27% to 1.44 x 10^6 (1.18% of the land area). Commercial forestry is estimated to reduce total runoff in South Africa by 3.2% (1 417 x $10^6 m^3$/yr) and MALf (the flow in the driest three months of the average year) by 7.8% (101 x $10^6 m^3$/yr). A likely range in the reduction of MAR is 1 000 to 1 500 x $10^6 m^3$/yr, based on different allocations of the flow reduction models.

The best estimate of 1 417 x $10^6 m^3$/yr is some 10% higher than the DWA (1986) estimate of 1 284 x $10^6 m^3$/yr but is 13% lower per unit plantation area at 98.7 mm/yr compared with the approximately 113.6 mm/yr over a plantation area of 1.13 x 10^6 ha (DWA, 1986).

This is also the first study to examine the effects on low flows and compare them with those on total flow. The differences can be substantial in catchments where most of the subcatchments (e.g. quaternary catchments) produce little or no low flow. An example is the Letaba River system where the afforestation of only 3.6% of the total area results in reductions of 8.8% and 28.1% in the total and low flows, respectively.

There are a number of key uncertainties which require that any estimate of the hydrological effects of plantations in South Africa has to be treated with caution. The most important is probably the uncertainties about the timing and extent of the reductions in streamflow in the large area of plantations with an annual rainfall of less than 900 mm (±63% of the total plantation area), and the absence of data to support a specific model for wattle.

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