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Forest evaporation models: relationships between stand growth and evaporation

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Abstract

The relationships between forest stand structure, growth and evaporation were analysed to determine whether forest evaporation can be estimated from stand growth data. This approach permits rapid assessment of the potential impacts of afforestation on the water regime. The basis for this approach is (a) that growth rates are determined by water availability and limited by the maximum water extraction potential, and (b) that stand evaporation is proportional to biomass and biomass increment. The relationships between stand growth and evaporation were modelled for a set of catchment experiments where estimates of both growth and evaporation were available. The predicted mean evaporation, over periods of several years, was generally within 10% of the measured mean annual evaporation (rainfall minus streamflow) when the model from one catchment was applied to other catchments planted with the same species. The residual evaporation, after fitting the models, was correlated with rainfall: above-average rainfall resulted in above-average evaporation. This relationship could be used to derive estimates for dry and wet years. Analyses using the models provide additional evidence that *Eucalyptus grandis* may be depleting groundwater reserves in catchments where its roots can reach the water table. The models are designed to be integrated into a plantation management system which uses a geographic information system for spatial analysis and modelling. The use of readily available growth parameters as predictor variables may reduce our dependence on intricate process-based models. This is seen as an efficient way of extrapolating existing catchment data — reflecting the impacts of forestry on water supplies across a range of sites, climatic zones and species. This approach has the potential for further development, especially in dealing with low flows and faster growing species. © 1997 Elsevier Science B.V.

1. Introduction

Water is one of the major factors restricting the expansion of agriculture, forestry and industry in South Africa. The growth of the forestry industry is restricted directly by the

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afforestation permit system (Van der Zel, 1990) which employs a reasonable but highly simplified model of the impacts of plantations on runoff, originally developed by Nänni (1970). Although this model has been adapted in the light of additional research data, it has some significant shortcomings:

1. Silvicultural practices have changed markedly with the introduction of intensive site preparation and fertilisation.
2. The introduction of new species, improved genotypes and hybrids has resulted in the widespread planting of fast growing trees. Rotations have been reduced from 20 or more years to as little as 8 years for eucalypt pulpwood.

One solution has been to use data from existing catchment experiments to develop more refined but fundamentally similar models (examples are Bosch and Von Gadow, 1990; Smith and Scott, 1992). These models are still based on analyses of the measured reduction in streamflow in afforested catchments with increasing age of the plantation, age being used as a substitute for stand development. Evaporation from forest stands is a function of stand structure and species characteristics, rather than age *per se* (Van Lill et al., 1980; Bosch and Hewlett, 1982). There is a need to develop enhanced evaporation models for afforested areas, new modelling approaches that will deal with changed silvicultural practices, faster growing species and genotypes, and inter-annual variability. At the same time these models must also meet the needs of planners for a sound basis for managing water resources. The aim of this study is to develop robust means of estimating forest evaporation that can be integrated into plantation planning and management systems.

Hydrological research in South Africa into the impacts of afforestation has been aimed almost entirely at providing improved data for policies and legislation for regulating afforestation to conserve water supplies (e.g Van Lill et al., 1980; Van Wyk, 1987; Bosch and Von Gadow, 1990; Smith and Scott, 1992). Little research has been done to determine how plantations can be managed to conserve and utilise water resources efficiently and effectively. Virtually all plantation research in South Africa has been directed towards manipulating growth and yield through varying silvicultural regimes, site preparation and fertilisation (e.g. Schönau, 1985; Wessels, 1987; Payn et al., 1988; Schafer and Groenewald, 1990; Herbert, 1991). Few studies have attempted to relate plantation growth to water resources, except for Boden's (1991) preliminary work. Yet irrigation and fertilisation are complementary and fertilisation is of little or no benefit if water is the limiting factor (Landsberg, 1986; Sands and Mulligan, 1990; Nambiar, 1990/91). Water management can no longer be neglected and will be a key factor in the success, or failure, of afforestation of marginal sites, and in agro-forestry projects which are typically situated in the drier, more drought-prone areas.

The basis of the approach proposed in this paper is that there is a relationship between tree growth and tree water use. This statement embraces two fundamental postulates:

1. that growth rates are determined by water availability and limited by the maximum water extraction potential (Squire et al., 1987); and
2. that stand evaporation is proportional to the leaf area which, *inter alia*, is related to the biomass (Bosch and Hewlett, 1982; Calder, 1992).

The normal approach has been to model how water availability affects growth (e.g. Calder, 1992). We propose, however, to stand the normal hydrological approach on its head: to predict stand evaporation from data on stand growth rather than predicting growth from data on moisture availability. A strength of this approach is its explicit recognition that tree growth integrates all the environmental factors that influence it on a particular site, including water availability, rooting conditions and soil fertility. It also holds the promise that the large databases on tree growth held by the commercial forest companies could be used to model forest evaporation at a wide variety of locations around the country. It follows then that the basic land unit of the model will be the 'site', an internally homogenous unit with regard to its tree growth potential.

This paper describes an analysis of data on the relationships between annual evaporation and stand development to test the hypothesis that stand structure — as expressed through height, stand basal area (m^2 ha^{-1}) or stand volume (m^3 ha^{-1}) — is proportional to the estimated evaporation. The goal was to find suitable models for projecting trends in evaporation for plantations, based on growth projection models and silvicultural regimes (e.g. stand densities and ages for thinning or felling). Just as the growth projection models project mean annual growth to estimate timber yields (rather than the actual annual growth for a particular year), the evaporation models should also predict mean trends in evaporation.

2. Methods

2.1. Selection of catchments

The choice of catchment studies for this study was limited by two factors: (a) the range of afforested catchments with reliable data on rainfall and runoff; and (b) the availability of data on the growth, planting density and thinnings of the plantation compartments in the catchments.

This reduced the list of available catchments for this study to those given in Table 1. More detailed information on those catchments is given by Nänni (1971), Van Lill et al. (1980) and Van Wyk (1987).

2.2. Tree growth data

The choice of models for estimating site index, growth and yield modelling was limited by the variables measured to assess stand growth for the compartments in hydrological research catchments (Tables 1 and 2). In most cases only mean or dominant height data at a given age were available. Recent data for Mokobulaan B were obtained from a field survey during October 1992. Data for Catchment III at Cathedral Peak were taken from an enumeration carried out in 1979. Data for Bosboukloof were obtained from a full enumeration in 1979 (D. Versfeld, unpublished data), and for Mokobulaan A from a survey of leaf area and biomass (D. Versfeld, unpublished data). Data for the other catchments at Jonkershoek were extracted from the plantation inventory database

Table 1

Data on the experimental catchments used in the analysis of the relationship between tree growth and increase in annual evaporation (rainfall – streamflow). Catchment data from Nänni (1971), Van Lill et al. (1980), Van Wyk (1977, 1987), Bosch and Hewlett (1982), and from unpublished catchment records and climate data held at Jonkershoek Forestry Research Centre

Name	Location	Area	Rainfall	Species	Planting date
Bosboukloof	Jonkershoek, Western Cape	200.9 ha, 122.49 ha planted	1940–1990, 1528.4 mm yr^{-1} (gauge 5B)	*Pinus radiata* and *Pinus canariensis* (0.4 ha)	planted between 1937 and 1940, clearfelled from 1979 to 1981
Biesievlei	Jonkershoek	27.20 ha, 100% planted	1940–1990, 1297.2 mm yr^{-1} (gauge 19B)	*P. radiata*	planted 1948
Lambrechtsbos A	Jonkershoek	31.2 ha, 29.40 ha planted	1940–1990, 1476.7 mm yr^{-1} (gauge 10B)	*P. radiata*	planted 1972
Lambrechtsbos B	Jonkershoek	65.5 ha, 48.56 ha planted	1940–1990, 1476.7 mm yr^{-1} (gauge 10B)	*P. radiata*	planted 1963
Cathedral Peak III	Drakensberg, Natal	142 ha, 117.86 ha planted	1958–1979, 1586.7 mm yr^{-1}	*P. patula*	planted 1958, partially burnt and replanted in 1964, burnt in a fire in 1980
Mokobulaan A	Eastern Transvaal	26.2 ha, 100% planted	1957–1988, 1164.3 mm yr^{-1}	*Eucalyptus grandis*	planted 1969, clearfelled 1985
Mokobulaan B	Eastern Transvaal	34.6 ha, 100% planted	1957–1988, 1171.0 mm yr^{-1}	*P. patula*	planted 1971
Westfalia D	Northern Transvaal	39.6 ha, ±35 ha planted	1975–1990, 1476.6 mm yr^{-1}	*E. grandis*	planted 1983

Table 2
Growth data for the plantations in the experimental catchments

Catchment	Species	Stand growth data
Bosboukloof	*P. radiata*	calculated SI_{20} range 18.5–25.3
Biesievlei	*P. radiata*	age 30 years, ht = 28.5 m, $SI_{20} = 23.0$
Lambrechtsbos A	*P. radiata*	age 15 years, ht = 13.0 m, $SI_{20} = 15.3$
Lambrechtsbos B	*P. radiata*	age 19 years, ht = 19.6 m, $SI_{20} = 20.2$
Cathedral Peak III	*P. patula*	part 16 and part 21 years, $SI_{20} = 17.7$
Mokobulaan A	*Eucalyptus grandis*	age 5 years, ht = 27.3 m, $SI_{20} = 43.2$
Mokobulaan B	*P. patula*	age 22 years, $SI_{20} = 24.7$
Westfalia	*E. grandis*	age 9.6 years, ht = 33.6 m, $SI_{20} = 46.7$

printouts provided by the forester, Mr A. Liebenberg. Data for Westfalia were kindly provided by the forester, Mr S. Klaasen.

2.3. Site index models

Site index (SI) is a measure of the growth potential of the stand and is used as a parameter in the stand growth and yield projection models. There are many site index models for the major commercial forest tree species in South Africa. The site index models listed below were chosen because they used only the available data on tree height (mean or dominant) at a known age, thus SI = *f*(age, ht), and did not require additional parameters. The data used to estimate the site indexes, or obtained for each catchment, are summarised in Table 2.

The following site index models were used.

Pinus patula (Kotze, personal communication, 1992):

$$SI = ht^{([\{1-\exp(-0.038273*\ age)\}/0.5348801]^{0.854442})}$$

where ht = height in metres and age = age in years.

Eucalyptus grandis (Kotze, 1991):

$$SI = ht * \{[(1-\exp[-0.05454 * \ ageind])/(1-\exp[-0.05454 * \ ageref])]^{0.8217}\}$$

where ageind = 20 for an SI_{20} and ageref = age at time of survey.

Pinus radiata (Grey, 1988):

$$SI = \exp[\log_e(ht)/\{([20/age]^{-0.03526}) * (\exp[-3.0907 * (1/age - 0.05)])\}]$$

with abbreviations as indicated above; $\log_e$ = natural logarithm.

2.4. Stand growth models

The formulae for utilisable standing timber volume (SV, $m^3\ ha^{-1}$) and the basal area (BA, $m^2\ ha^{-1}$) were chosen because they used only the available data: stand density (stems $ha^{-1} = n$), site index (m), age (years) and height (m). The height for a given age was projected by rearranging the site index formula and using the calculated, or known, site index value for that compartment.

Pinus radiata:
BA (Grut, 1971):

$$BA = 1.302 * \mathrm{ht} + 0.0009042 * ht * n - 0.0160 * ht^2 + 0.009237 * n + 0.04501 * \mathrm{age}^2 - 0.000003624 * n^2 - 1.868 * \mathrm{age} - 3.789$$

SV (Bredenkamp, 1992):

$$SV = \exp[2.404 + 0.0979 * SI - 31.936/\mathrm{age} + 0.346 * \log_e(n)]$$

Eucalyptus grandis (Kotze, 1991):

$$\log_e(BA) = -16.8860 * (1/\mathrm{age}) + 0.1513 * \log_e(n) + 0.8218 * \log_e(\mathrm{ht}) + 1.4264 * \log_e(n)/\mathrm{age} + 1.6347 * \log_e(\mathrm{ht})/\mathrm{age}$$

$$\log_e(SV) = -2.06351 + 0.105497 * \log_e(n) + 1.164169 * \log_e(\mathrm{ht}) - 0.211295 * (\log_e(n)/\mathrm{age}) + 0.600957 * (\log_e(\mathrm{ht})/\mathrm{age}) + 0.923717 * \log_e(B)$$

$$\text{where } \log_e(B) = -13.1284 * (1/\mathrm{age}) + 0.19695 * \log_e(n) + 0.74452 * \log_e(\mathrm{ht}) + 1.21796 * (\log_e(n)/\mathrm{age}) + 0.72628 * (\log_e(\mathrm{ht})/\mathrm{age})$$

Pinus patula (H. Kotze, personal communication, 1992):

$$\log_e(BA) = 2.561649 - 77.099070/\mathrm{age} + 0.390732 * \log_e(\mathrm{ht}) + 9.152063 * \log_e(n)/\mathrm{age} + 3.648891 * \log_e(\mathrm{ht})/\mathrm{age} + 0.090597 * (n_t/n_a) * (\mathrm{age}_t/\mathrm{age})$$

where n_t = density before thinning; n_a = density after thinning; age_t = age at last thinning.

$$SV = \exp(-0.036186 * \log_e(n) + 0.746320 * \log_e(\mathrm{ht}) + 1.085385 * \log_e(BA) - 0.424246 * \log_e(n)/\mathrm{age})$$

The tree height (m), standing volume ($m^3\,ha^{-1}$), total volume (m^3), stand basal area ($m^2\,ha^{-1}$) and total basal area (m^2) were calculated for the stands in each catchment, using the above formulae and the available data on planting density and thinnings. Bosboukloof has about 28 compartments (management units) planted and thinned on different dates, so growth data were calculated for each compartment. *Pinus canariensis*, which comprised about 0.3% of the area, was treated as equivalent to *P. radiata*. The area weighted mean for the growth data for the whole catchment was calculated for each year. A similar approach was used for Catchment III at Cathedral Peak where there were ten management compartments, four of which were burnt out during a wildfire in 1964 and replanted.

2.5. Evaporation

Total annual evaporation (transpiration plus interception) was estimated from the difference between rainfall and streamflow for each hydrological year: April to March for the winter rainfall region (Jonkershoek) and October to September in the summer rainfall region (the other catchments). Rainfall data were taken from the records for the raingauge considered most representative of the catchment rainfall. It was not possible to obtain areally averaged rainfall or data for more than one raingauge in all the catchments, and a consistent value across all catchments was preferred. This should not result in significant errors at the time scale of one year used in these analyses.

2.6. Evaporation and tree growth

The relationships between evaporation and stand growth were analysed using standard linear regression. The dependent and independent variables were tested in linear and non-linear (log and square-root transformed) forms. Multiple linear regressions were also tested with various combinations of the independent variables. The final selection of the most appropriate forms and models was based on two criteria: (a) the fit of the individual model based on the R-squared value; and (b) the model form that gave the most consistently good fit for all the catchments. All the statistical analyses were done using PC-SAS Version 6.04 (SAS, 1990).

3. Results

A simple logarithmic transformation of the dependent or independent variables, or both, generally gave the best regression fits. Non-linear, polynomial and multivariate regression models were tested but simple linear regression models were found to give as good a fit.

3.1. Stand growth and evaporation

The most consistent relationship between evaporation and stand growth took the form of a power function $\mathrm{ET} = ax^b$, where the dependent variable x was a standard growth parameter (height, basal area or utilisable volume). When the exponent b is less than 1, this gives a function which rises to an asymptotic value so that the ratio of evaporation to the stand growth parameter (e.g. mm evaporation per m^2 of basal area per ha) declines as the stand grows. The natural vegetation (grassland or shrubland) which the growing plantation suppressed did not change structurally between planting and canopy closure. Once the tree canopy closed there was little or no understorey vegetation, even after thinnings. Thus the changes in evaporation are due to the developing plantation.

Year-to-year variation and dry and wet cycles in rainfall were important factors in the poor fit of the regression models. The coefficient of variation of the rainfall in the different catchments ranged from 14% to 19%, and likewise for evaporation, because evaporation was calculated from rainfall minus streamflow. An analysis of the relationships between rainfall and evaporation found strong positive correlations for most catchments (Table 3).

Table 3
Correlations between evaporation and rainfall and residual evaporation (after fitting regression models) and with deviations from the mean rainfall

Catchment	Correlations	
	Evaporation with rainfall	Residual evaporation with deviation from mean rainfall
Bosboukloof	0.82^{**}	0.89^{**}
Biesievlei	0.63^{**}	0.81^{**}
Lambrechtsbos A	0.81^{**}	0.82^{**}
Lambrechtsbos B	0.85^{**}	0.87^{**}
Cathedral Peak III	0.50^{*}	0.46^{*}
Mokobulaan A	0.87^{**}	0.66^{*}
Mokobulaan B	0.49 ns	0.79^{**}
Westfalia D	0.90^{**}	0.70^{*}

*: $p < 0.05$;
**: $p < 0.01$;
ns: $p > 0.05$.

A similar analysis of residual evaporation (after model fitting) and deviation from mean rainfall also found strong positive correlations. There also were unexplained trends in the catchments themselves. For example, streamflow in the Lambrechtsbos A catchment declined from planting in 1972 until the 1980–1982 period and subsequently showed a steady increase, with only minor fluctuations in response to variations in rainfall. Lambrechtsbos B, Bosboukloof and Biesievlei, adjacent catchments, did not show this kind of trend.

3.2. Stand basal area and evaporation

The models using stand basal area gave the best mean fit over all the catchments analysed but gave poor results in some cases (Table 4). The regression relationships for the Jonkershoek catchments were generally poor, the strongest being based on evaporation expressed as a percentage of the rainfall (Table 5). The primary reason for the poor fit was the strong influence of one or more low values for evaporation. So, for example, in

Table 4
Models of the relationship between stand basal area (ba, $m^2\,ha^{-1}$) and catchment evaporation (et = rainfall − streamflow)

Catchment	Model	Statistics
Bosboukloof	$et = 931.0851*(ba + 1)^{0.05259}$	$n = 38$, $F = 1.64$, $R^2 = 0.04$, $p = 0.21$
Biesievlei	$et = 569.9890*(ba + 1)^{0.15143}$	$n = 33$, $F = 15.04$, $R^2 = 0.33$, $p < 0.01$
Lambrechtsbos A	$et = 785.4669*(ba + 1)^{0.14696}$	$n = 19$, $F = 3.27$, $R^2 = 0.16$, $p = 0.09$
Lambrechtsbos B	$et = 867.2470*(ba + 1)^{0.08228}$	$n = 28$, $F = 2.51$, $R^2 = 0.09$, $p = 0.12$
Cathedral Peak III	$et = 713.6006*(ba + 1)^{1.15144}$	$n = 22$, $F = 30.65$, $R^2 = 0.61$, $p < 0.01$
Mokobulaan A	$et = 872.2760*(ba + 1)^{0.11103}$	$n = 10$, $F = 33.85$, $R^2 = 0.81$, $p < 0.01$
Mokobulaan B	$et = 966.4284*(ba + 1)^{0.06335}$	$n = 11$, $F = 5.55$, $R^2 = 0.33$, $p = 0.04$
Westfalia D	$et = 903.6078*(ba + 1)^{0.10231}$	$n = 8$, $F = 4.93$, $R^2 = 0.45$, $p = 0.07$

Table 5

Regression models of the relationship between stand growth and evaporation expressed as a percentage of the annual rainfall (PCEt), except for Westfalia where no model could be fitted ($p > 0.15$). Key to abbreviations: vol = volume (m^3 ha^{-1}); ba = basal area (m^2 ha^{-1}); ht = height (m)

Catchment	Model	R^2 (probability)
Bosboukloof	$PCEt = 58.1643 + 3.4139*\log_e(vol + 1)$	$n = 38, F = 24.31, R^2 = 0.40, p < 0.01$
Biesievlei	$PCEt = 53.55633 + 4.636669*\log_e(vol + 1)$	$n = 33, F = 52.02, R^2 = 0.63, p < 0.01$
Lambrechtsbos A	$PCEt = 67.3868 + 1.0992*(ba + 1)$	$n = 19, F = 7.01, R^2 = 0.29, p < 0.04$
Lambrechtsbos B	$PCEt = 71.1577 + 2.2139*\log_e(vol + 1)$	$n = 28, F = 12.44, R^2 = 0.32, p < 0.01$
Cathedral Peak III	$PCEt = 50.4983 + 4.2732*\log_e(vol + 1)$	$n = 22, F = 15.65, R^2 = 0.44, p < 0.01$
Mokobulaan A	$PCEt = 86.1246 + 0.04070*(vol)$	$n = 10, F = 16.70, R^2 = 0.68, p < 0.01$
Mokobulaan B	$PCEt = 75.3538 + 5.5796*\log_e(vol + 1)$	$n = 11, F = 27.87, R^2 = 0.76, p < 0.01$
Westfalia D	$et = 628.5437*(ht + 1)^{0.2130}$	$n = 8, F = 6.71, R^2 = 0.53, p = 0.04$

Bosboukloof and Biesievlei there was a dry period from 1968 to 1974 during which the expected increase in evaporation, based on rainfall, was close to zero or negative but the basal area was near its maximum. In some catchments the fit was relatively good, with coefficients of determination (R^2) of 0.60 or more (Tables 4 and 5). The initial regression models for the Mokobulaan catchments were not statistically significant; but when the analysis was restricted to the period from planting till when the streams dried up (1979 for Mokobulaan A and 1982 for Mokobulaan B), the fit improved significantly.

3.3. *Comparisons between catchments planted with the same species*

A proper test of the performance of these models would require similar data on tree growth and evaporation from an entirely independent catchment experiment. This was not possible, so the models were tested by examining how accurately the model for one catchment (e.g. Bosboukloof) could predict the mean evaporation for another catchment planted with the same species (e.g. Biesievlei), using the growth data for that other catchment.

3.3.1. *Pinus patula*

Two catchments were planted with *Pinus patula*: Catchment III at Cathedral Peak and Catchment B at Mokobulaan. These catchments differed quite markedly, however, with Cathedral Peak having an annual rainfall of about 1590 mm and Mokobulaan B 1170 mm. The constants in the regression models also differed markedly (Tables 4 and 5). After afforestation there was a much greater increase in evaporation at Cathedral Peak, about 500 mm (Fig. 1), compared with an increase of about 150 mm for Mokobulaan B (Fig. 2). These differences were reflected in the relatively poor predictions for the Cathedral Peak model when used on Mokobulaan B, especially for the period 1972–1981, and vice versa (Table 6).

3.3.2. *Eucalyptus grandis*

The climates of the Mokobulaan A and Westfalia D catchments (both planted with *Eucalyptus grandis*) differ, with Westfalia D receiving about 1476 mm and Mokobulaan A

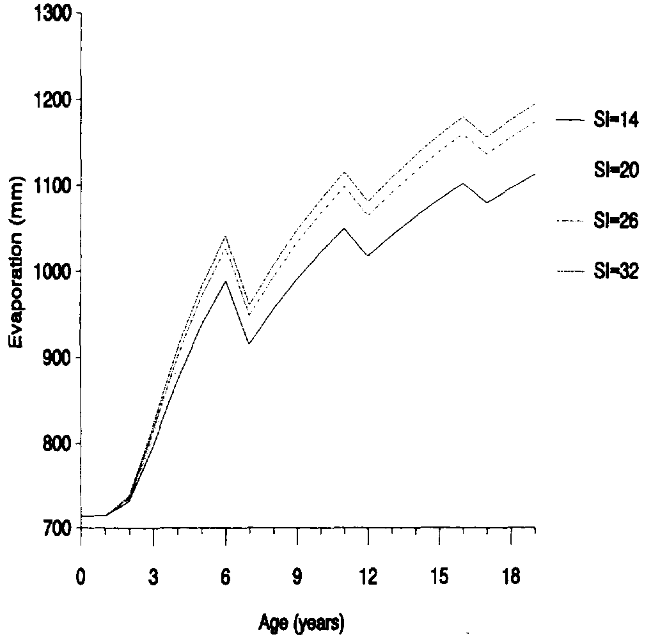

Fig. 1. Relationship between stand age and projected evaporation based on the model for *Pinus patula* at Cathedral Peak. The breaks in the curves are the result of thinnings. SI = site index (dominant height in metres) at the age of 20 years.

about 1164 mm per year (Table 1). The potential growth rates for *Eucalyptus grandis* were also higher at Westfalia, with an $SI_{20} = 46.7$ as against 43.2 for Mokobulaan A (Table 2). The projected evaporation, based on the regression model for *Eucalyptus grandis* (Table 4), reached a maximum of about 1400 mm per year at Mokobulaan A (Fig. 3). Both the Mokobulaan A and the Westfalia D models gave good estimates of mean evaporation for the period 1970–1978, within 5% of the calculated values (Table 7).

3.3.3. *Pinus radiata*

A similar comparison of the four Jonkershoek catchments (Table 8), all planted with *Pinus radiata*, shows that the models for both Bosboukloof and Lambrechtsbos B gave acceptable predictions of the other's evaporation. The regression model for Lambrechtsbos A consistently gave the highest estimates of evaporation when applied to the other catchments. The biggest differences were those for the Biesievlei catchment, where the predictions from the other catchment models are 16–35% higher than was measured as rainfall minus streamflow. Similarly, the Biesievlei model underestimated the measured evaporation for the other catchments by 15–28%. The measured evaporation data (rainfall minus streamflow) for Biesievlei were lower (941 mm yr^{-1}), despite being 100% afforested, than those for Lambrechtsbos A with 1104 mm yr^{-1} (94% afforested), Lambrechtsbos B with 1119 mm yr^{-1} (74% afforested) and Bosboukloof with 1108 mm yr^{-1} (56% afforested). The differences in the modelled evaporation were consistent with these differences in measured evaporation. The growth figures were not consistent with the

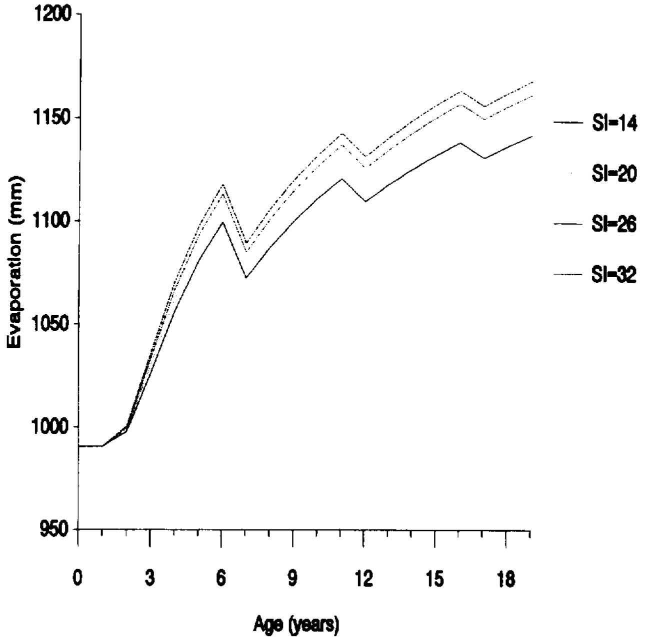

Fig. 2. Relationship between stand age and projected evaporation based on the model for *Pinus patula* at Mokobulaan. Breaks in the curves are the result of thinnings. SI = site index (dominant height in metres) at the age of 20 years.

lower water use of trees in Biesievlei, however. Biesievlei had the highest growth potential of $SI_{20} = 23.0$ compared with Lambrechtsbos A, $SI_{20} = 15.3$, and Lambrechtsbos B, $SI_{20} = 20.2$ (Table 2). The intercept value (pre-afforestation evaporation) for the Biesievlei model also was lower (±600 mm yr^{-1}) than the 800–900 mm yr^{-1} for the other three

Table 6

A comparison of mean values for annual evaporation calculated from rainfall minus streamflow and estimated from models developed for catchments afforested with *Pinus patula*. Comparisons are given for two different periods for Mokobulaan B, where the stream dried up completely in 1982. Differences are expressed as a percentage of the calculated evaporation. Basal area is in m^2 ha^{-1}, volume in m^3 ha^{-1}

Catchment	Period	Comparison	Source	Mean (difference)
Cathedral Peak III	1965–1979	Cathedral Peak III	rainfall – streamflow	1090.9
			basal area	1089.1 (−0.2%)
			volume	1093.7 (+0.3%)
		Mokobulaan B	basal area	1152.6 (+5.7%)
Mokobulaan B	1971–1981	Mokobulaan B	rainfall – streamflow	1059.2
			basal area	1056.3 (−0.3%)
		Cathedral Peak III	basal area	887.5 (−16.2%)
	1982–1988	Mokobulaan B	rainfall – streamflow	1117.8
			basal area	1150.4 (+3.0%)
		Cathedral Peak III	basal area	1083.6 (−3.1%)

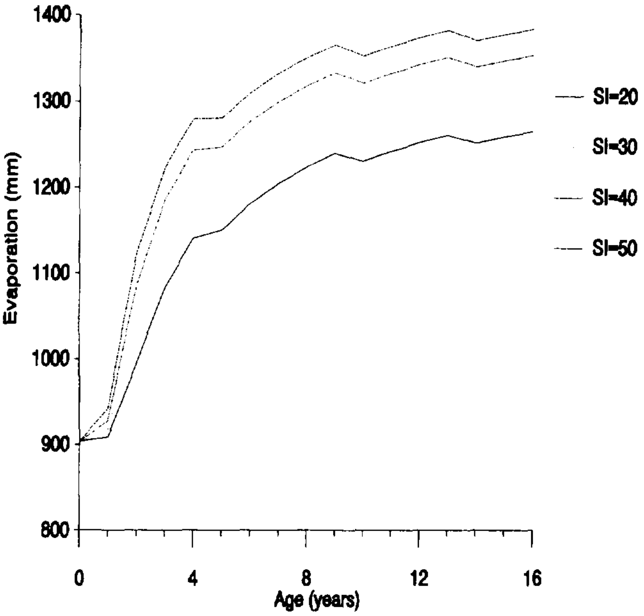

Fig. 3. Relationship between stand age and projected evaporation based on the model for *Eucalyptus grandis* at Mokobulaan. Breaks in the curves are the result of thinnings. SI = site index (dominant height in metres) at the age of 20 years.

Jonkershoek catchments (Table 4), although they all supported similar shrubland communities prior to afforestation.

4. Discussion

The simple linear regression models used in this study differ from the sigmoid functions used by Smith and Scott (1992) and the non-linearizable Chapman–Richards function

Table 7

A comparison of mean values for annual evaporation calculated from rainfall minus streamflow and estimated from models developed for catchments afforested with *Eucalyptus grandis*. Comparisons are given for two different periods for Mokobulaan A, where the stream dried up completely in 1979. Basal area is in $m^2 ha^{-1}$

Catchment	Period	Comparison	Source	Mean (difference)
Mokobulaan A	1970–1978	Mokobulaan A	rainfall – streamflow	1180.9
			basal area	1184.7 (+0.3%)
		Westfalia D	basal_area	1197.6 (+1.4%)
	1979–1985	Mokobulaan A	rainfall – streamflow	1031.0
			basal area	1309.9 (+27.1%)
		Westfalia D	basal area	1314.3 (+27.5%)
Westfalia D	1984–1990	Westfalia D	rainfall – streamflow	1176.5
			basal area	1150.4 (−2.2%)
		Mokobulaan A	basal area	1134.1 (−3.6%)

Table 8

A comparison of mean values for annual evaporation calculated from rainfall minus streamflow and estimated from models developed for catchments afforested with *Pinus radiata*. Differences are expressed as a percentage of the calculated evaporation. Basal area is in m^2 ha^{-1}, volume in m^3 ha^{-1}

Catchment	Period	Comparison	Source	Mean (difference)
Biesievlei	1951–1980	Biesievlei	rainfall – streamflow	941.2
			basal area	927.9 (–1.2%)
		Lambrechtsbos A	basal area	1269.6 (+34.9%)
		Lambrechtsbos B	basal area	1134.3 (+20.5%)
		Bosboukloof	volume	1100.5 (+16.9%)
Lambrechtsbos A	1975–1990	Lambrechtsbos A	rainfall – streamflow	1133.0
			basal area	1116.0 (–1.5%)
		Biesievlei	basal area	808.5 (–28.2%)
		Lambrechtsbos B	basal area	1055.6 (–6.8%)
		Bosboukloof	volume	1046.7 (–7.6%)
Lambrechtsbos B	1966–1990	Lambrechtsbos B	rainfall – streamflow	1119.0
			basal area	1106.2 (–1.2%)
		Biesievlei	basal area	885.4 (–20.9%)
		Lambrechtsbos A	basal area	1213.7 (+8.5%)
		Bosboukloof	volume	1083.5 (–3.2%)
Bosboukloof	1940–1979	Bosboukloof	rainfall – streamflow	1108.1
			volume	1104.0 (–0.4%)
		Biesievlei	basal area	936.9 (–15.4%)
		Lambrechtsbos A	basal area	1272.1 (+14.8%)
		Lambrechtsbos B	volume	1083.7 (–2.2%)

used by Bosch and Von Gadow (1990). These studies simply regressed the reduction in streamflow, or the increase in evaporation, on stand age and needed a sigmoid function to describe the trends. The growth projection models used in this analysis already have a sigmoid form so that a sigmoid transformation was redundant and consistently gave a poorer fit.

4.1. Stand growth and evaporation

The models based on stand growth were able to predict mean annual evaporation over a period of 5 or more years within 10% of the measured evaporation. The primary reason for the poor fit (R^2) was that the models do not include variables which would correct the estimates of evaporation for variations in evaporative demand or soil or groundwater storage. In this approach the change in storage was treated as ≈ 0. However, the strong positive correlations between rainfall and evaporation and between the deviations in rainfall and evaporation (Table 3) show that this was not correct. Evaporation was higher than expected in wet years and lower than expected in dry years because streamflow did not change in direct proportion to rainfall. The balance was taken up by the storage component in these catchments, increasing in wet years and decreasing in dry years.

The effects of year-to-year variations in evaporative demand and rainfall cycles could be factored out by expressing evaporation as a percentage of the rainfall (Smith and Scott, 1992) or using an antecedent wetness index. Percentages are not appropriate for a model requiring absolute values because they are specific to the amount of rainfall and to characteristics such as rainfall/runoff ratios in a particular catchment. The same kinds of difficulty limit the use of an antecedent wetness index. The strong correlations between deviations in rainfall and evaporation suggest that a second stage model, to adjust evaporation based on the deviation of the rainfall from the mean, could be used to adjust the predictions for dry or wet years. This possibility needs to be taken further, especially as atmospheric demand would be higher in dry years and the trees may use more water than would be estimated from this second stage model. Further analyses of the residual variations in evaporation for some catchments (e.g. Mokobulaan B and Cathedral Peak III) are needed to improve the fits of their second stage models.

4.2. Comparisons between catchments with the same species

4.2.1. Eucalyptus grandis

Evidence from studies of the Mokobulaan A catchment suggests that the eucalypts were accessing and depleting groundwater stores (Dye and Poulter, 1991; Lesch and Scott, 1993). When the measured evaporation and the projected evaporation were compared for the period after runoff had ceased at Mokobulaan A (1979–1985), the differences ranged from 24 to 27% (Table 7). The difference between the measured evaporation and the projected evaporation ranged from 0 to 530 mm more than the annual rainfall. This did not seem to be simply a model error because the predictions of both the Westfalia D and Mokobulaan A models for Westfalia D were within 5% of the measured values (rainfall minus streamflow) for the Westfalia D catchment. Thus the model predictions were consistent for periods when streamflow continued, despite differences between the catchments. The difference between predicted and measured evaporation falls well outside the 95% confidence limits (mean ± 90 mm), so it seems that deep soil and groundwater were used by the plantation. The total deficit from 1979 to 1985 was about 1950 mm, and a reduction of this magnitude could explain why it took about five years before streamflow returned to normal after clearfelling (Lesch and Scott, 1993). It is also likely that the estimated 'excess' from the growth model was conservative since the runoff was already markedly reduced in the third year after planting (Van Lill et al., 1980; Lesch and Scott, 1993). These findings have serious implications. For example, even clearfelling may not be sufficient to restore flow for a year or more once the streams in an area have dried up completely.

4.2.2. Pinus patula

The predictions for the period 1982–1988 at Mokobulaan B, after the stream dried up, suggest that the pines may have been using about 3% more water than was supplied in rainfall (the calculated evaporation = rainfall because there was no streamflow). The predicted evaporation from the stand exceeded the rainfall by about 33 mm per year or about 227 mm over the period 1982–1988. This deficit was much less, so we would predict that the stream should require only a short period to start flowing normally again. The estimated reduction also lies well within the 95% confidence limits (mean ± 80 mm per year) of the regression model and so the difference may not be real. This estimate also assumes that transpiration by the trees was not limited by soil water availability, but *Pinus patula* does experience seasonal water stress in similar situations (P. Dye, personal communicastion, 1994). On the other hand, the estimate may be conservative as the runoff was already significantly reduced in the fourth year after afforestation (Lesch and Scott, 1993).

It is not clear why afforestation with *Pinus patula* resulted in an increase in evaporation of about 150 mm per year at Mokobulaan B compared with about 500 mm per year for Cathedral Peak III (Figs 1 and 2). The climates and environments do differ quite markedly. Cathedral Peak is situated at an altitude of 2080 m in the Natal Drakensberg, while Mokobulaan is on the Eastern Transvaal escarpment at 1396 m. The rainfall at Cathedral Peak is about 1590 mm yr^{-1} (Table 1) and the evaporation about 940 mm yr^{-1} (runoff ± 650 mm yr^{-1}, Bosch and Hewlett, 1982), compared with Mokobulaan B with 1075 and 820 mm yr^{-1} respectively (mean runoff for 1956–1968 = 254 mm yr^{-1}, Nänni, 1971). Bosch and Von Gadow (1990) estimated that there was a similar increase in evaporation after afforestation at Cathedral Peak, namely about 570 mm yr^{-1}.

The Mokobulaan catchments had unusually low rainfall/runoff ratios prior to planting (catchment A = 0.22, B = 0.17) (Nänni, 1971). Catchment A, with *Eucalyptus grandis*, dried up eight years after planting and catchment B, with *Pinus patula*, ten years after planting (Lesch and Scott, 1993). During a recent drought even the unplanted control catchment dried up completely (F.W. Prinsloo, personal communication, 1992), having done so once before in 1970 (Nänni, 1971). This suggests that the hydrology of these catchments needs to be studied more carefully to assess the size and nature of the groundwater stores and whether the streamflow over the weir is an accurate measurement of the flow from the catchment.

4.2.3. *Pinus radiata*

One explanation for the differences in evaporation, actual and modelled, between Bosboukloof, Lambrechtsbos A and B and Biesievlei is that the Biesievlei catchment is not entirely leakproof in terms of either inputs or outputs. If the trees had access to additional water, they could have used more than was measured from the difference between rainfall and streamflow. There is no explanation, at present, for the high estimated evaporation by the Lambrechtsbos A model, and this deviation should be explored further.

5. Conclusions

The modelling approach adopted in this study does appear to be a viable alternative to those based solely on time since treatment. Although they estimate only mean reductions in runoff, the 95% confidence limits can be used as upper and lower bounds on evaporation. Alternatively, a second stage model can be used which estimates the evaporation for a given year on the basis of the deviation from the mean rainfall. Assuming, as do most streamflow reduction models, that net changes in storage over a number of years will be ≈ 0, changes in mean runoff can be calculated from the change in evaporation. Thus, if the mean rainfall for a catchment was 1400 mm yr^{-1} and the runoff 400 mm yr^{-1}, the evaporation must be $\approx$ 1000 mm yr^{-1}. If the projected evaporation under 90%

afforestation, based on data on stand growth potential, is about 1300 mm yr^{-1}, then the streamflow will decrease by about 200 mm yr^{-1}. If the confidence limits are ±100 mm yr^{-1}, then it is highly likely that streamflow will cease during droughts. These calculations can be extended to examine the potential impacts of droughts on flow reductions, using the 95% confidence limits or second stage models.

As noted in the introduction, these models were not intended to predict evaporation for a particular year, but to project the expected mean evaporation from a plantation. This is entirely appropriate for some applications. For example, the current model, derived by Nänni (1970), simply estimates the mean reduction in runoff for a specified rotation, regardless of species, differences in silvicultural practices and growth rates. Growth-based models now allow for different species (eucalypt or pine) and different silvicultural regimes.

The approach is also appropriate for a plantation management system where decisions are based on growth projection models. These models also project the mean growth of the stand over time, with no allowance for the impacts of, for example, drought on growth. The projected growth for a stand may be adjusted as a result of enumerations, usually done prior to thinning, which indicate that the actual growth rate is faster or slower than projected. These adjustments will also be reflected in the estimated evaporation.

Issues such the impacts of plantations on low flows, the risk of loss of growth and mortality during droughts, and the potential benefits of breeding trees that are more efficient in water use are very important to the forest industry. A different modelling approach will be needed to deal with soil moisture budgeting and the influence of soil water availability and climatic conditions on evaporation. The models described here cannot meet those needs, nor are they intended to. But this is the first time, as far as we have been able to establish, where evaporation models have been based on stand growth functions. It is also the first time in South Africa that the predictions from models based on data from one catchment have been tested on different catchments planted with the same species. The results provide some evidence that our reasoning, that this approach should lend itself to extrapolation to other sites, was sound. The results also provide direct quantitative support for the recognition by Van Lill et al. (1980) and Bosch and Hewlett (1982) that differences in stand growth rates can influence trends in streamflow reduction over time. More studies are required, though, to show that the same relationships hold on sites with, for example, lower annual rainfall and other species.

We recognise that the variables of interest to silviculturalists, e.g. tree height and utilisable volume — which we would prefer to use because of their availability throughout afforested areas — are generally only indirectly related to the important driving parameters for water use, namely leaf area and leaf area index. There are other surrogate variables which are more directly related to leaf area, for example annual increment (Linder, 1985), and these relationships need to be tested. A more important consideration is that trees are also known to vary in their water-use efficiency, and in how this efficiency changes under drought stress and after application of fertilizer (Waring, 1983; Gholz et al., 1990; Nambiar, 1990/91). We believe that these issues can be addressed and that growth-based water-use modelling shows sufficient merit to be developed further.

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References

Boden, D.I., 1991. The relationship between soil water status, rainfall and the growth of *Eucalyptus grandis*. S. Afr. For. J., 156: 49–55.

Bosch, J.M. and Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol., 55: 3–23.

Bosch, J.M. and Von Gadow, K., 1990. Regulating afforestation for water conservation in South Africa. S. Afr. For. J., 153: 41–54.

Bredenkamp, B., 1992. Yield potential for Urbans Industries (Pty) Ltd. Unpublished report for Urban's Industries (Pty) Ltd.

Calder, I.R., 1992. A model of transpiration and growth of Eucalyptus plantation in water-limited conditions. J. Hydrol., 130: 1–15.

Dye, P.J. and Poulter, S.A.G., 1991. An investigation of sub-soil water penetration in the Mokobulaan research catchments, south-eastern Transvaal. S. Afr. For. J., 161: 31–34.

Gholz, H.I., Ewel, R.C. and Teskey, R.O., 1990. Water and forest productivity. For. Ecol. Manage., 30: 1–18.

Grey, D.C., 1988. A site index model for *Pinus radiata* in the Southern Cape. In: Von Gadow, K. (Editor), Research Contributions to Plantation Forestry — Festschrift in honour of Professor A. van Laar, Forestry Faculty, University of Stellenbosch.

Grut, M., 1971. Estimating yields from *Pinus radiata* stands. For. S. Afr., 12: 41–48.

Herbert, M.A., 1991. The influence of site factors on the foliar nutrient content of *Eucalyptus grandis* in Natal. S. Afr. For. J., 156: 28–34.

Kotze, H., 1991. Growth–yield prediction methodology. Unpublished Honours Project, Faculty of Forestry, University of Stellenbosch.

Landsberg, J.J., 1986. Experimental approaches to the study of the effects of nutrients and water on carbon assimilation by trees. Tree Physiol., 2: 427–444.

Lesch, W. and Scott, D.F., 1993. A report on the effects of afforestation and deforestation on streamflow and low flows at Mokobulaan. Report FOR-DEA 620, Department of Water Affairs and Forestry, Pretoria.

Linder, S., 1985. Potential and actual production in Australian forest stands. In: J.J. Landsberg and W. Parsons (Editors), Research for Forest Management. CSIRO, Australia, pp 11–35.

Nambiar, E.K.S., 1990/91. Management of forests under nutrient and water stress. Water, Air, and Soil Pollut., 54: 209–230.

Nänni, U.W., 1970. Trees, water and perspective. S. Afr. For. J., 75: 9–17.

Nänni, U.W., 1971. The Mokobulaan research catchments. S. Afr. For. J., 78: 5–13.

Payn, T.W., De Ronde, C. and Grey, D.C., 1988. Phosphate fertilisation of mature *Pinus radiata* stands. S. Afr. For. J., 147: 16–25.

Sands, R. and Mulligan, D.R., 1990. Water and nutrient dynamics and tree growth. For. Ecol. Manage., 30: 91–111.

SAS, 1990. SAS/STAT® User's Guide Version 6, 4th edition. SAS Institute Inc., Cary, NC, 2 volumes.

Schafer, G.N. and Groenewald, W.H., 1990. Fertilisation of *Pinus radiata* on some marginal sites in the southern Cape. S. Afr. For. J., 154: 36–40.

Schönau, A.P.G., 1985. Basic silviculture for the successful establishment of eucalypt plantations, with special reference to Eucalyptus grandis. S. Afr. For. J., 135: 4–9.

Smith, R.E., 1992. Simple empirical models to predict reductions in annual and low flows resulting from afforestation. Report to Department of Water Affairs, Forestek, CSIR.

Smith, R.E. and Scott, D.F., 1992. The effects of afforestation on low flows in various regions of South Africa. Water SA, 18: 185–194.

Squire, R.O., Attiwill, P.M. and Neales, T.F. 1987. Effects of changes in available water and nutrients of growth, root development and water use in *Pinus radiata* seedlings. Aust. For. Res., 17: 99–111.

Van der Zel, D.W., 1990. The afforestation permit system. Information Leaflet No. 1, Department of Environment Affairs, Pretoria.

Van Lill, W.S., Kruger, F.J. and Van Wyk, D.B., 1980. The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. J. Hydrol., 48: 107–118.

Van Wyk, D.B., 1977. Die invloed van bebossing met *Pinus radiata* op totale jaarlikse afvoer van die Jonkershoek strome. Unpublished MSc Thesis, University of Stellenbosch.

Van Wyk, D.B., 1987. Some effects of afforestation on streamflow in the Western Cape Province, South Africa. Water SA, 13: 31–36.

Waring, R.H., 1983. Estimating forest growth and efficiency in relation to canopy leaf area. Adv. Ecol. Res., 13: 327–353.

Wessels, N.O., 1987. Silviculture of pines. In: K. von Gadow, D.W. van der Zel, A. van Laar, A.P.G. Schönau, H.W. Kassier, P.W. Warkotsch, H.F. Vermaas, D.L. Owen and J.V. Jordaan (Editors), Forestry Handbook. South African Institute of Forestry, Pretoria, pp. 95–105.