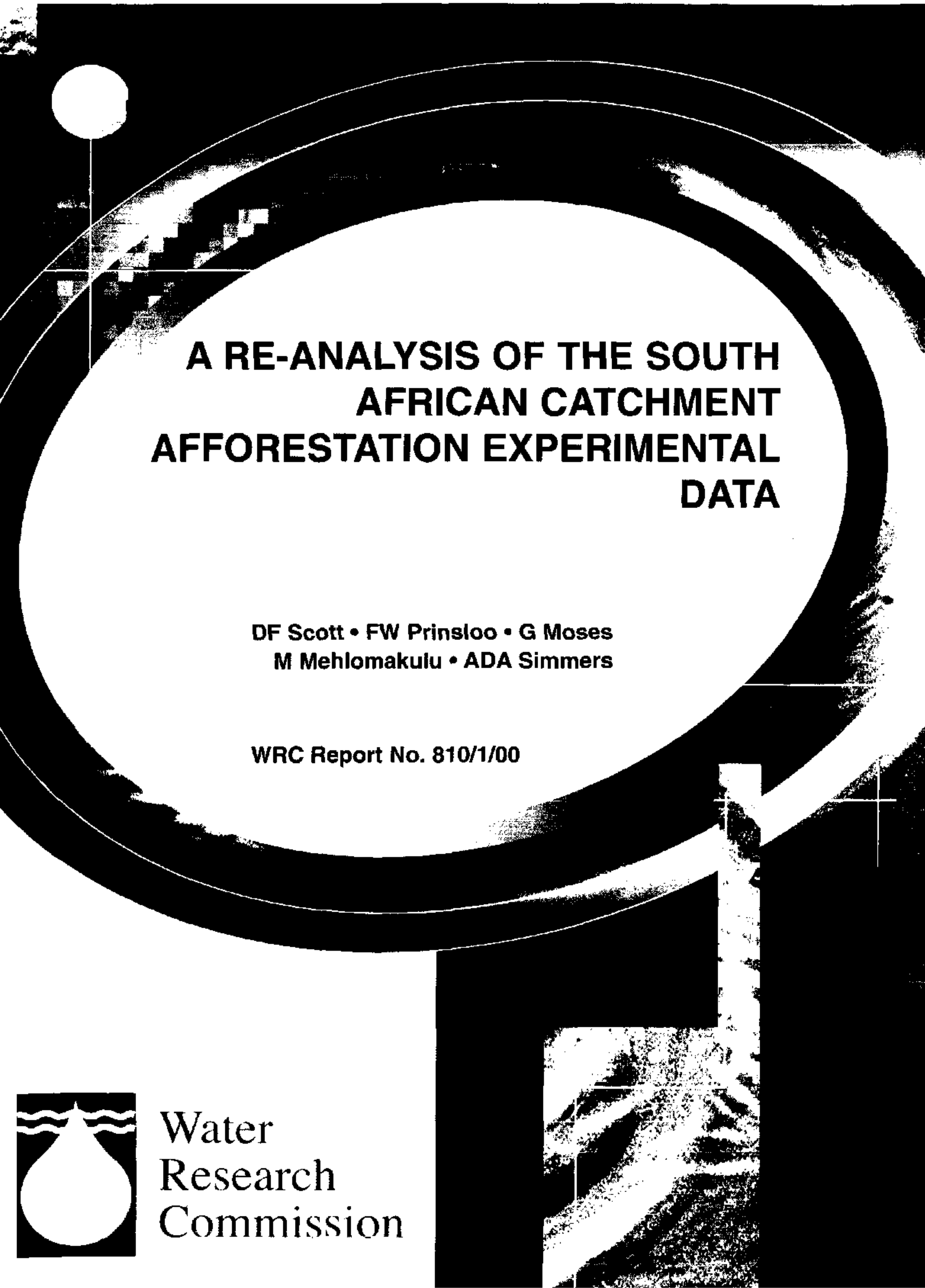

A RE-ANALYSIS OF THE SOUTH AFRICAN CATCHMENT AFFORESTATION EXPERIMENTAL DATA

DF Scott • FW Prinsloo • G Moses
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WRC Report No. 810/1/00

Water
Research
Commission

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Report to the Water Research Commission

by

DF Scott, FW Prinsloo, G Moses, M Mehlomakulu and ADA Simmers

CSIR Division of Water, Environment and
Forestry Technology
Stellenbosch

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EXECUTIVE SUMMARY

INTRODUCTION

Forestry is an important agricultural activity in South Africa accounting for 6.3% by value of the country's gross agricultural output in 1996/97 (FOA, 1998). This primary industry in turn supports a large forest products industry that made up 7.4% of South Africa's gross manufacturing output in 1996/97 (FOA, 1998). At the same time forestry is estimated to have a consumptive water use equivalent to 7.5% of the country's available water resources (Scott *et al.*, 1998), and forestry continues to receive much attention because of the water consumption of timber plantations. The expansion of the forest industry has been regulated since 1972 on the basis of its estimated water resource effects. The provisions of the new National Water Act will make forestry liable to pay for water use as a streamflow reduction activity, and this has placed increased attention on the quantification of the water use of timber plantations, and the accuracy with which such use can be estimated. For this reason it is important that full use is made of the information contained in the long-running catchment afforestation experiments.

The South African afforested catchment experiments were initiated over sixty years ago, with a long term vision of multiple replication of sites and species over many decades. The historical nature of the data collected, the length of record and the range of sites involved make the experiments unique and invaluable. Although most of the experimental data have already been analysed to some extent or another, there was a need to consolidate the experimental data, to re-work the data in a uniform and consistent way, and to generalise the results, particularly with respect to new information needs. We can now review this large body of data to assess the composite picture which has emerged to date with respect to the influence of forestry on streamflow.

This project for the Water Research Commission sought to:-

- Update and prepare the complete body of experimental afforestation data.
- Produce a definitive review of the South African catchment afforestation experiments based on a complete and consistent analysis of the available data.
- Consolidate our understanding of the nature of and our ability to predict streamflow reductions caused by forestry.
- Provide a definitive baseline against which modelling efforts can be tested.

METHODS

The study looked at a series of paired catchment comparisons. This method involves the long-term monitoring of streamflow from pairs of catchments before and after a major vegetation change in one of them. The treatment effect is primarily measured against a baseline provided by the relationship between the two catchments before treatment. The method is applicable to both afforestation and clearfelling treatments. The statistical test for treatment effect is by means of the dummy variable technique of regression analysis.

Weekly streamflow volumes were used as the computational unit, which provides some smoothing when comparing different catchments, but at the same time provides for robust statistics because of the large sample numbers. The effects on both total flows and low flows were analysed separately: low flows being defined as those weeks when flow was below the 75th percentile exceedance level in the control catchment.

Seventeen experiments were analysed altogether, from data generated in 13 treated catchments, and comprising 12 planting experiments and five clearfelling experiments; 12 of which experiments were with pines and five with eucalypts. The research sites are at five locations across the forestry (i.e. high rainfall) zone of South Africa, namely, Jonkershoek near Stellenbosch in the Western Cape, Cathedral Peak in the Drakensberg, Mokobulaan and Witklip on the Mpumalanga escarpment and Westfalia near Tzaneen. Additional data, although incomplete, from two small catchments at Ntabamhlope near Estcourt in KwaZulu-Natal are also included.

RESULTS

For each successfully analysed experiment the estimated effects on total and low flows are standardised to a 10% level of planting or clearing and plotted against time in two figures. The seasonal effects are illustrated by plotting the mean flow reductions or increases for each month of the year, generated over many years while the plantations were mature. The results are also tabulated.

The initiation of flow reductions (onset of significant reductions after planting) varies widely depending on the stature of the competing native vegetation and the rate at which catchments are dominated by the plantation crop. The pine plantations in tall fynbos in the Western Cape and in high altitude grasslands in the Drakensberg usually took several years to have a clear impact on streamflow (up to 6 years). However some pine crops, e.g. Lambrechtsbos-A in Jonkershoek and Mokobulaan B in Mpumalanga had an early effect on streamflows (within 3 years). Eucalypts have an earlier impact on streamflows, within 2 to 3 years. Under drier conditions this was still true, though here (Ntabamhlope) the timber crop also had the benefit of full site preparation prior to planting.

Once reductions are significant they generally become larger quite quickly, reaching peak or near peak reductions fairly early in the rotation. Peak reductions under pine are reached around 15 years of age and at least 5 years earlier under eucalypts. At the drier Ntabamhlope site flows ceased completely in the fourth year after planting, which was also a dry hydrological year. It seems to be generally true that dry conditions will accelerate the desiccation of the catchment after planting.

Peak reductions per year (mean over 5 consecutive years) range widely under pines from 17 to 67 mm/10% and from 37 to 41 mm/10% planted under eucalypts. The absolute reductions at Ntabamhlope have only been measured for a few years but would be much smaller than the figures for other eucalypt plantings. Peak absolute reductions relative to expected flows occur at variable stages within the rotation depending on site specific conditions. Relative reductions, also over a five year window, have a narrower peak, from 6.6 to 10%/10% under pines to 9.8 to 10%/10% planted under eucalypts.

A new finding from this up-to-date analysis is that flow reductions are definitely diminished towards the end of longer timber rotations, and this is true of both pines and at least one eucalypt experiment. Obviously this trend is clearest in the longer term experiments. The diminution of final flow reductions (mean over last 5 years measured) compared to the highest 5 year mean reductions ranges from zero (no change over time, usually in short term experiments) to 60% and 50% less, for absolute and relative measures respectively. The single eucalypt experiment in which this trend was observed was confounded by a partial clearing (~10% cleared along the stream) prior to the restoration of streamflows. However, the small area that was cleared is not likely to account for the large change in flow reductions (48%).

DISCUSSION

Understanding the drivers of afforestation effects

The most important determinant of the flow reductions is water availability. Wet catchments with a high water availability have the highest flow reductions. This is probably because water demand is generally greater than supply in South African conditions (situations where supply is unlimited are rare in this country). Good examples of this point are Cathedral Peak II and Tierkloof where 5-year mean estimated peak reductions were 67 and 54 mm/10%, respectively. From this it also follows that wet years are those in which the highest reductions are measured. This point is illustrated by Mokobulaan A & B that were both dry for the latter half of the rotations but because of differences in rainfall the estimated 5-year mean maxima were 41 and 17 mm/10% respectively.

Conversely, low water availability can lead to bigger relative reductions, earlier in the rotation, e.g. Mokobulaan B under pine reached a 100% reduction in 12 years under a dry cycle and the dry Ntabamhlope catchments, planted to a hardy eucalypt, reached 100% reductions in the fourth year of the rotation.

Fit of the CSIR empirical models

The empirical curves developed by the CSIR are currently used to estimate the probable impact of afforestation schemes. The additional experiments analysed in this study offer an opportunity to verify these models. It is clear from the study that the general empirical models provide only an average and long-term estimate of the reductions caused by afforestation. Age is far from being a complete predictor of streamflow reductions as indicated by the large year by year variation in effects on flow.

There is a substantial variation in the key components; time to initiation of flow reductions after planting, size of reductions in individual years, and size of effects in the later years of long rotations.

In broad terms the results show that the *curves often underestimate* the early effects of afforestation, especially for the longer rotation pine experiments in Jonkershoek and the eucalypt crops at the drier Ntabamhlope site. Furthermore, the curves are asymptotic, remaining at a maximum for the latter part of a rotation. This shape seems to be realistic for short rotation crops and in drier areas, where water demand will usually exceed supply for the duration of the rotation. For the longer rotation crops (probably over 15 and 20 years for eucalypts and pines *respectively*) on more humid sites the flow reduction curves will need to be modified to replicate the shape of a growth curve, to give a gradually declining influence of the trees on streamflow.

Understanding the long rotation reversals in effects

This study has established for South African plantation forestry conditions that flow reductions are not sustained at an asymptote indefinitely. As plantations mature so they have a diminished effect on streamflows than earlier in the rotation. The timing of these decreases is not adequately understood at this stage. The pattern of streamflow effects in the catchments resembles the pattern, though with different time scales, of the measured transpiration cycle of young *Eucalyptus grandis* stands in Mpumalanga, of the response in streamflow to fire in, and regrowth of, mountain ash (*Eucalyptus regnans*) forest in Australia and over-mature fynbos in the Western Cape, and the regrowth of mature indigenous scrub forest at Tzaneen, Northern Province.

The results support a hypothesis that the catchment is a large reservoir formed of deeply weathered soil and therefore acts as a buffer for short-term changes in components of the hydrological cycle. Large increases in evaporative losses, such as occur after the establishment of fast growing plantations into grassland, draw on the reservoir of the catchment as well as current year rainfall. The effects of afforestation on streamflow therefore become lagged. In other words, changes in storage of water within the catchment vary from year to year and are important in smoothing the response in streamflow to change in vegetation. Once evaporative losses decline such as occurs with maturing trees or after clearfelling or fire, the catchment reservoir must first be recharged before full streamflow recovery will be recorded.

CONCLUSIONS

There is large variability in the results of these experiments: both natural variability caused by site and species differences and *climatic variation and the sequence of climatic* events. The responses in two similar catchments to specific climatic events or the inability of the statistical models to replicate a seasonally specific response provides a source of statistical variability. Streamflow response is an integral of all hydrological processes, and streamflow generation is a complex process and probably unique for each catchment - hence this is a source of variation that is not, and is likely to remain, inadequately understood.

Consequently,

1. There is a need for long periods of data in order that one can develop a full

picture of land use effects through the natural variations that obscure the picture.

2. Also, for the above reasons, replication is vital. A single catchment cannot provide proper insight, nor can a single climatic sequence provide an understanding of how a response will vary under different rainfall cycle. Replication therefore involves different species, sites and timing.

The initial onset of flow reductions has been underestimated for the bulk of pine plantations. Whereas a long lag before flow reductions become significant has become the general expectation, many of the additional experiments analysed here show that flow reductions can be important from an earlier stage in the rotation. As most forestry in South Africa is now in second or higher rotations and there is much less competing vegetation at the time of replanting, long lags prior to there being significant effects on streamflow are probably most unlikely.

Over longer rotations, there is a negative relationship between plantation age and streamflow reductions. This means that during the later stages of a long sawlog rotation some degree of replenishment of soil water stores occurs, to counter-balance net losses from storage in the early part of the rotation. The implication of this finding is that the hydrological effects of long rotation crops has probably been over-estimated in the past, and the hydrological effects of short rotation crops, such as eucalypt pulp and mining timber, has been under-estimated (because of a lag between evaporation and streamflow response).

RECOMMENDATIONS

The project has produced a large series of secondary data sets; the estimated flow reductions or increases over time following afforestation or clearfelling respectively. An aspect that can be readily researched from this base is the relationship between flow reductions and rainfall year (or general catchment wetness), i.e. the effects of forestry in wet and dry years and through wet and dry cycles. There is considerable speculation over this relationship which is of particular relevance for the estimation of supply to run-of-river water users and calculations of the reserve. It is also important to establish the nature of this relationship in order to establish a proper baseline against which the realism of modelling efforts can be tested.

The current project has not investigated the environmental variables that might add explanation to observed variation in forestry effects between different catchments and different years. Amongst the environmental drivers, for example, that might be tested for an influence on observed effects are rainfall, temperature, soil depth or tree rooting.

The major part of the current project went into data preparation, and relatively little time was spent on analysis. However, now that all the data has been prepared, and especially as the secondary data (i.e. observed effects) are available, there are several additional aspects that may be studied at relatively little extra cost. These are listed in brief below.

- Clarify the effects of forestry by further analysis, specifically characterising the onset and extent of the diminished effects late in the rotation, and determine the influence within each catchment of annual rainfall characteristics.

- Relate the secondary results to broader environmental determinants, for example relating observed effects to Et, rainfall or temperature, to soil depth or tree rooting.

- Investigation of patterns in the flow duration curves through the forestry rotations.

- Refinement of the empirical flow reduction models to incorporate the increased understanding developed through the additional analyses accomplished by this project.

- Setting up generalised limits to the effects of forestry within various climatic conditions for different types of forestry, as a basis for checking the results of deterministic modelling efforts.

ACKNOWLEDGEMENTS

The project was funded by the Water Research Commission whose assistance is gratefully acknowledged. The experiments were established by the research arm of the erstwhile Department of Forestry and its successors, most recently the Chief Directorate of Forestry of the Department of Water Affairs and Forestry, which continues to fund the maintenance of part of the original research network. The Ntabamhlope catchments were monitored since planting as part of a Water Research Commission project and the data were made available through the assistance of the School of Bio-engineering and Environmental Hydrology of the University of Natal and the Computing Centre for Water Research.

We salute the vision and persistence of the early South African forest hydrologists, CL Wicht, UW Nänni and others, who planned and established these experiments, and the many technicians and researchers who maintained the equipment and collected the data over the years with care and dedication.

The project was guided by a Water Research Committee whose assistance is greatly acknowledged. Members of this committee were:

Mr H Maaren : *Water Research Commission (Chairman)*
Dr G C Green : *Water Research Commission*
Dr G Jewitt : *University of Natal*
Prof R E Schulze : *University of Natal*
Dr P J Dye : *CSIR*
Mr J M Bosch : *CSIR*
Dr T L Simelane : *Department Water Affairs & Forestry*
Dr D W van der Zel : *Department Water Affairs & Forestry*
Mr E A Nel : *Department Water Affairs & Forestry*
Dr J Scotcher : *SAPPI*
Mr P Gardiner : *Mondi Forest*
Mr L J Esprey : *ICFR*
Dr L J du Preez : *Water Research Commission (Secretary)*

Capacity Development Aspects

This project served to develop skills in several young, permanent and temporary staff members. Two affirmative action bursars, Adrian Combrinck and Linda Arendse, worked in the Stellenbosch offices of the CSIR on data reduction: learning to understand the charts from rain-gauges and streamflow recorders, digitising these charts, checking data and doing data summaries.

Godfrey Moses, a long-serving technical assistant in the offices of the CSIR in Stellenbosch, received further training in data reduction, checking and editing, and also developed skills in data manipulation with the SAS package. As a tutored learning experience, he performed the paired catchment analysis using SAS for the Cathedral Peak experiments.

Mandla Mehlomakulu, a recent geography graduate, was trained in the use of the SAS statistical software and its use to perform regression analysis. He worked on the preliminary analysis of the Jonkershoek catchment experiments before departing to pursue post-graduate training at the University of Cape Town. Although he was not able to follow the project right through to completion, the training and practical experience will certainly be of longer term value to him.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

LIST OF APPENDICES

LIST OF MAPS

LIST OF PLATES

LIST OF TABLES

LIST OF FIGURES

Figures **Page**

1. INTRODUCTION AND RATIONALE FOR THE STUDY

Forestry is an important agricultural activity in South Africa accounting for 6.3% by value of the country's gross agricultural output in 1996/97 (FOA, 1998). Forestry in turn supports a large forest products industry that made up 7.4% of South Africa's gross manufacturing output in 1996/97 (FOA, 1998). At the same time forestry is estimated to have a consumptive water use equivalent to 7.5% of the country's available water resources (Scott *et al.*, 1998), and forestry continues to receive much attention because of the water consumption of timber plantations. The expansion of the forest industry has been regulated since 1972 on the basis of its estimated water resource effects.

Research into water use of timber plantations commenced in 1937 with the establishment of the most comprehensive network of catchment experiments for any land use in South Africa. These experiments have been analysed individually over the last half century by a variety of methods (Wicht and Schumann, 1957, Nänni, 1970a; Bosch, 1979; Van Lill *et al.*, 1980; Van Wyk, 1987). The results have been of great use in estimating the size and nature of the effects of forestry and in providing the scientific basis for the regulation of the growth of the forest industry. For this purpose general predictive models were developed, based on the results of the catchment experiments (Nänni, 1970b; van der Zel, 1995) or using them to check the model output, for example the Pitman model (Midgley *et al.*, 1981) and ACRU (Schulze and George (1987)).

However, the methods used in the original analyses though were often limited. Statistical techniques have since improved. Previously, weak correlations with rainfall were the basis of some predictions, and conservative bounds were placed on predictions which may have under-estimated afforestation effects. The various sets of results are therefore not strictly comparable. A need existed to treat all the data in a standard and unified way, and to review the whole body of experimental data.

Furthermore, models such as ACRU and VTI are being proposed for use in predicting afforestation effects, but these need a real baseline against which the performance of the models can be tested. One needs to have a thorough understanding of what the real effects of afforestation are before one can truly evaluate the performance of simulation models.

The afforestation experiments remain the definitive set of data on the effects of forestry on stream flow, and much information remains untapped within these data. The empirical flow reduction models which are currently widely used in South Africa, can be expanded and adjusted using results from the catchment experiments. But this would require a consistent re-working of all the data and a synoptic over-view of what the results reveal.

Project Objectives

Produce a definitive review of the South African catchment afforestation experiments based on a complete and consistent re-working of this large resource of unique and valuable data.

Clarify the issues around afforestation effects on streamflow which are currently being debated, specifically providing more information on the effects of forestry on low flows and drought-period flows.

Provide a baseline against which modelling efforts can be tested.

1.1 SYNOPTIC OVERVIEW

The catchments experiments of the then Department of Forestry were started in 1937, primarily motivated by the need to assess the hydrological effects of afforestation in South Africa. At the time there was considerable confusion on the issue of whether trees were beneficial or detrimental to water supplies. The experimental catchments were designed to investigate treatment effects by the paired catchment method. Over time, the research network was extended from Jonkershoek in the Western Cape to Cathedral Peak in the Drakensberg, Mokobulaan and Witklip on the Mpumalanga escarpment and Westfalia near Tzaneen.

The timber species planted in the research catchments were those considered best suited to the site from amongst the recommended sawlog species. Thus the catchments in Jonkershoek were all planted to *Pinus radiata*, *Pinus patula* was planted in the high altitude catchments at Cathedral Peak, both *P. patula* and *Eucalyptus grandis* were planted at Mokobulaan and *E.grandis* at Westfalia estate. All the research plantations were established and tended according to standard sawlog silvicultural prescriptions of the Department of Forestry. This means they were thinned (the density of trees in the stands was reduced) at regular intervals to reduce competition between trees within the stand. As the product was to be saw-timber the trees were also pruned to increase the length of the knot-free bole.

The catchments are all located in high rainfall regions of South Africa and are at the wetter end of the rainfall range of forestry sites in South Africa. Catchments were all planted to different extents, and this generally represents the normal plantable area. Thus steep and rocky slopes were excluded, as were a chain-width strip along perennial streams. In specific individual cases, entire catchments were afforested as part of the experimental treatment.

1.2 THE SIGNIFICANCE OF THE DATA: VALUE AS A BASELINE

The afforested catchment experiments represent the most extensive and detailed measurement of the hydrological effects of a land use change in South Africa. The South African catchment experiments are probably unique in the world in that they measure the effects of man-made plantations rather than deforestation of native forest; the length of continuous record is exceptional (over sixty years for some catchments in Jonkershoek) and the broad range of climate and soil conditions represented.

Already much more is known about the effects of forestry on streamflow than is known of any other land use. But, the value of the long-term and high quality hydrological data is also important.

- in providing a baseline for the development and testing of hydrological models; and
- as a resource toward understanding fundamental hydrological functioning of headwater catchments that form the backbone of water production in South Africa

1.3 REPRESENTATIVENESS OF THE RESEARCH CATCHMENTS

As stated earlier, the research catchments are located in the wetter end of the range of rainfall for forestry sites in South Africa. This is apparent from a comparison of the distribution of forestry by rainfall zone in Table 1 with the research catchment characteristics shown in Tables 3, 4, 5, 6 and 7. Of all the forestry in South Africa, less than 30% is located in areas where the mean annual precipitation (MAP) exceeds 1000 mm/yr. There was some logic in the initial site selection of the research catchments in that the method derives its results from measurements of streamflow. Should streamflow fail in a research catchment then the supply of data is thereby cut off. Nowadays, the absence of research catchments in the drier range of forestry sites is a disadvantage in that the bulk of forestry areas are not directly represented by the catchment experiments, and the effects of forestry in these drier zones is a subject on which there is great speculation.

Table 1 The area of the primary plantation types (wattle, pine and eucalypts) in South Africa in relation to the annual rainfall (from Scott *et al., 1998).*

Plantation type	Annual rainfall class (mm)	Area (ha)	Percent
Wattle	<800	9 010	8.12
	800-1000	95 000	85.58
	>1000	6 995	6.3
Total Wattle		111 005	
Pine	<800	109 738	13.38
	800-1000	434 820	53.04
	>1000	275 337	33.58
Total Pine		819 895	
Eucalypt	<800	31 414	6.21
	800-1000	338 529	66.93
	>1000	135 842	26.85
Total Eucalypt		505 785	
All species	<800	150 161	10.45
	800-1000	868 348	60.44
	>1000	418 174	29.11
TOTAL		1 436 684	

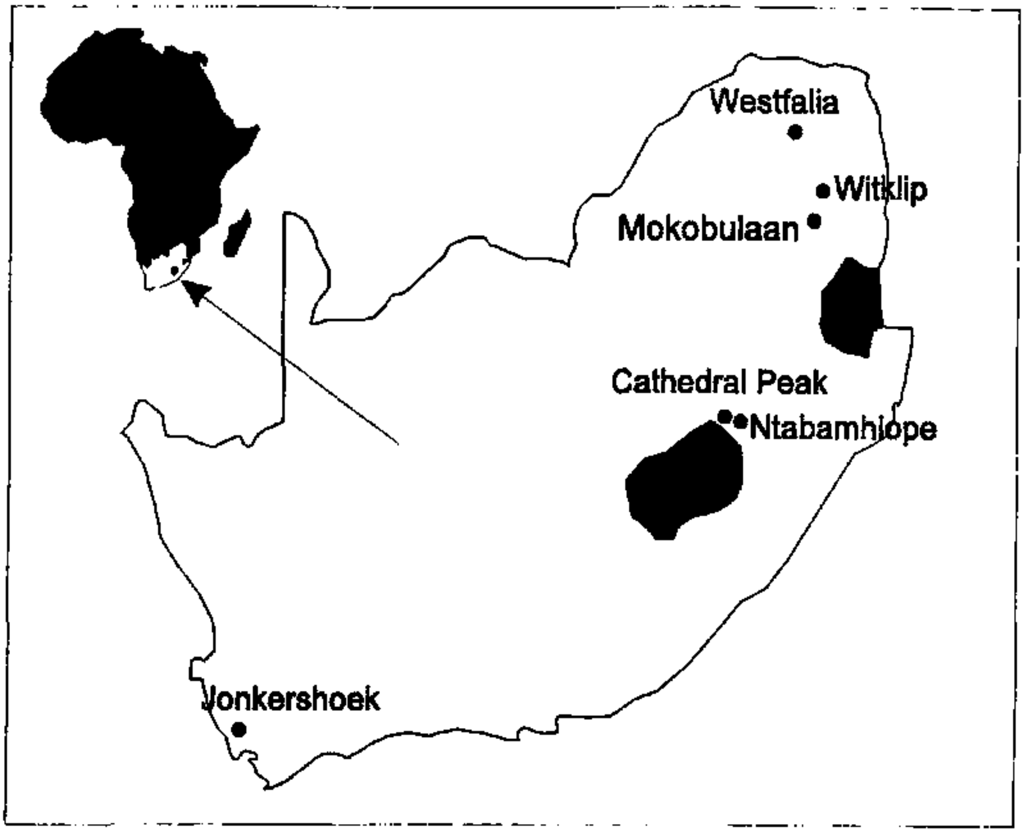
2. DESCRIPTION OF THE CATCHMENTS

2.1 GENERAL INTRODUCTION

The Fourth Empire Forestry Conference, which was held in South Africa in 1935, endorsed plans the then Government had to investigate "the influences of forests on water conservation and allied problems" (1935/36 *Annual Report* of the Division of Forestry). Towards the end of 1935 Dr. C.L. Wicht, to whom the task was entrusted, established a research station at Jonkershoek near Stellenbosch and started designing and initiated a research programme. The central idea of this "forest influences research", as Dr Wicht put it, was to determine how modification of the natural vegetation by different experimental treatments "such as afforestation, veld-burning, and complete protection" would affect "the natural circulation of water" (Wicht, 1939).

Each stream was to be studied independently and compared with itself before and after treatment. This was an adaption of the classical paired-catchment experiment method. It entailed gauging streamflow from a number of catchments over a calibration period of several years to establish relationships in streamflow between catchments.

The long-term plan was that Jonkershoek was to the first of a series of experimental sites that would cover the geographic range of the forestry areas in South Africa. As early as 1938 Cathedral Peak State Forest in the Drakensberg of KwaZulu-Natal had been identified as the site of the next experimental station and the first in the summer rainfall region. By the mid-1970s five experimental sites had been established for forest hydrological research (Map 1). The stations were, namely, *Jonkershoek* near Stellenbosch in the Western Cape, *Cathedral Peak* near Winterton, *Mokobulaan* on the Uitsoek State Forest between Nelspruit and Lydenburg, *Witklip* on Witklip State Forest near White River in Mpumalanga and, finally, the catchments on *Westfalia Estate* near Tzaneen in the Northern Province, established by the Hans Merensky Foundation in co-operation with the South African Forestry Research Institute.



Map 1
General location map of the hydrological catchment experiment sites in South Africa.

2.2 JONKERSHOEK

2.2.1 History

In 1935, Dr C L Wicht, to whom the task was entrusted to investigate the influence of forests on water conservation, started the Jonkershoek Forestry Research Station on the Jonkershoek State Forest.

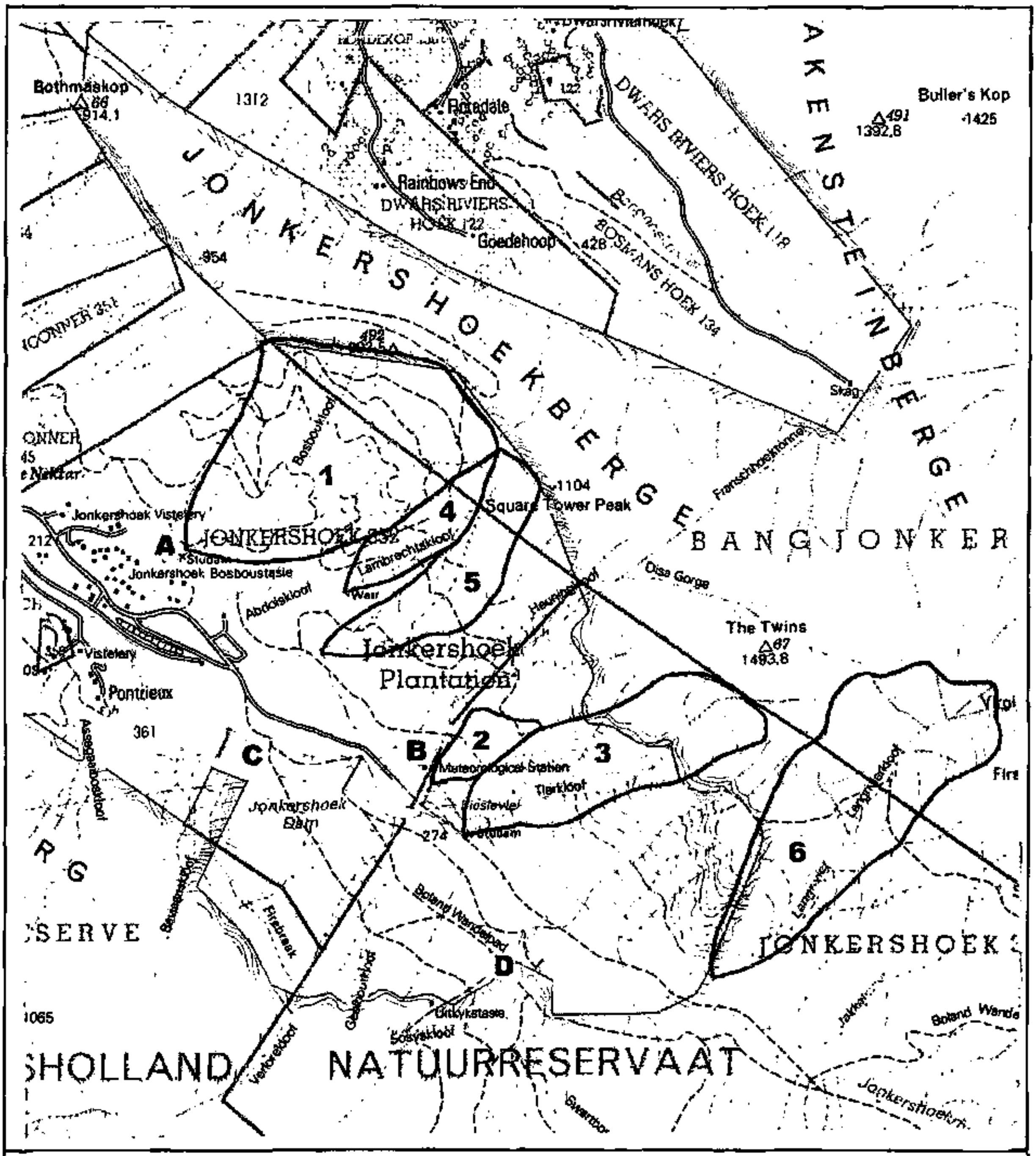
The farm Jonkershoek, from which the State Forest takes its name, was named after Jan Andriessen to whom it was granted by Governor Simon van der Stel in 1662. Andriessen had been a midshipman (jonkheer) in the service of the Dutch East India Company and was known as Jan de Jonkheer (Jonker). Jonkershoek and a number of adjoining properties constitute the Jonkershoek State Forest. A small section along the Eerste River is held on a 99-year lease, signed in 1933, from the Municipality of Stellenbosch.

A network of rain-gauges was installed, soil and vegetation surveys were completed and work commenced on the building of stream-guaging weirs. Planting of *Pinus radiata* in Bosboukloof commenced in 1937/38 with the other 5 catchments afforested in 8-year intervals. Langrivier was maintained in its natural state and served as control for the others.

2.2.2 Location

The Jonkershoek valley in the Western Cape Province is a long narrow valley that lies between the Stellenbosch Mountain (SW) and Jonkershoek Mountains (NE) and is enclosed by the Dwarsberg in the south-east (33°57'S; 18°55'E). All the streams in the valley form the tributaries of the Eerste River that flows through the town of Stellenbosch.

The six catchments used in this study lie on the south-west facing slopes of the Jonkershoek Mountains with altitudes ranging from 200 m to 1560 m a.m.s.l., and are named Bosboukloof, Lambrechtsbos A, Lambrechtsbos B, Biesievlei, Tierkloof and Langrivier (see Map 2).



Study Catchments: Jonkershoek Weather stations

Bosboukloof	no. 1	Herehuis	A
Biesievlei	no. 2	Biesievlei	B
Tierkloof	no. 3	Swartbrug	C
Lambrechtsbos A	no. 4	Swartboskloof	D
Lambrechtsbos B	no. 5		
Langrivier	no. 6		

Map ID and source: 3318DD, 1992: Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010

Map 2 Location and topography of the Jonkershoek study catchments.

2.2.3 Geology and Soils

The geology comprises of sandstone and quartzite (Early - Late Ordovician) with intermittent thin shale bands of Table Mountain Group (Lower Paleozoic Cape Supergroup)- mostly in the upper slopes and cliffs of the scarp. These are underlain by Cambrian (~500Ma) Cape Granite, which is found mostly on the lower slopes and valley floor. There are several talus screes of granite boulders plus sandstone debris (Van Wyk, 1987). The Jonkershoek valley is closed at the SE-end by the transverse Dwarsberg block fault.

The soils are complex and of mixed origin, derived primarily of mixed colluvial material from the above geological formations, with major forms being Hutton, Magwa and Nomanci (MacVicar *et.al*, 1977). These forms are acid sandy loams (pH 4.1 to 5.7), low in organic matter and in phosphorous (1 - 10 mg/kg, Bray 2 extraction). The soils have a low bulk density, high infiltration capacity and are well-drained. Soil depths range from roughly one to 2 m, but are underlain by unconsolidated or decomposed material that allows free drainage of water as well as exploration by tree roots.

2.2.4 Climate

The climate is of the humid mesothermal Mediterranean type with warm, dry summers (south easterly winds prevail) and cool wet winters with frequent cyclonic rains. The mean daily maximum temperature for February is 27.9°C while the mean daily minimum temperature for July is 5.9°C (Versfeld and Donald, 1991). Initially there were four meteorological weather stations throughout the catchment area: Herehuis, Biesievlei, Swartbrug and Swartboskloof. All stations measured temperature, relative humidity, sunshine hours, evaporation and rainfall. Wind speed and wind direction was measured at Biesievlei, Swartbrug and Swartboskloof, while barometric pressure was measured only at Swartboskloof. Only the weather station at Swartboskloof is still operating; the others having been closed down. The periods of record of the different weather stations are listed in Table 2.

Table 2 The periods of record of the weather stations in Jonkershoek.

Station	Started	Closed
Herehuis	1 April 1936	31 April 1999
Biesievlei	1 August 1945	1 April 1980
Swartbrug	1 August 1969	12 June 1975
Swartboskloof	18 June 1975	-

2.2.5 Rainfall

Annual rainfall for the research area averages 1390 mm of which 83% occurs in the 7 months of April to October, with the prevailing direction of rain-bearing winds being north-west. A detailed analysis of the rainfall sampling methods and rainfall patterns in Jonkershoek has been performed (Wicht *et al.*, 1969). The study shows a steep orographic rainfall pattern within the Jonkershoek valley. For example, raingauge 1A in the Herehuis weather station (244 m a.m.s.l.) has a mean annual precipitation (MAP) of 1180 mm, whilst raingauge 17B on Dwarsberg (1234 m a.m.s.l.) records the highest annual rainfall (3620 mm) in the country (Wicht, *et al.*, 1969). A general picture of the rainfall pattern in the research catchments can be found in Table 3.

2.2.6 Vegetation

The native vegetation of the area is a tall (2 - 3 m) open to closed fynbos shrubland dominated by *Protea neriifolia, Protea repens, Brunia nodiflora* and *Widdringtonia nodiflora.* Evergreen tall forests (>10 m) occur along streambanks with the dominant species being *Ilex mitis* and *Cunonia capensis* (Van Wilgen, 1982). The lower slopes were usually Protea scrub, with dwarf ericoid scrub on the upper slopes and reed-like restionaceous communities on the plateaus and crests.

The indigenous forest was confined mainly to the riparian zones of permanent streams. An aerial photograph of the valley taken in 1938 (Plate 1), indicates that only the Tierkloof, Langrivier and Bosboukloof catchments had well-defined indigenous forests along major parts of the riparian zones. At the other catchments, namely Lambrechtsbos A and B, and Biesievlei, only small pockets of indigenous forests occurred along the streambanks. In Plate 2, taken in 1949, the riparian zones left open in Bosboukloof during afforestation can clearly be seen. Plate 3, taken in 1967, shows the riparian zones in Tierkloof that were left unplanted. The Lambrechtsbos A catchment was not afforested yet. By 1977 (Plate 4) all catchments have been afforested, with the trees in Lambrechtsbos A about 4 years old. Plate 5, taken in 1988, shows the Bosboukloof catchment two years after the wildfire that swept through the upper part in 1986. It had been clear felled during 1979 - 1983. The Biesievlei catchment that was clear felled between 1984 and 1986 can also be seen.

Table 3 The physical characteristics and key variables of the **Jonkershoek** research catchments used in this study

Variables / Characteristics	**Bosboukloof**	**Biesievlei**	**Tierkloof**	**Lambrechts-Bos A**	**Lambrechts-Bos B**	**Langrivier**
Area (ha)	*200.9*	*27.2*	*157.2*	31.2	65.5	245.8
Percentage afforestation (%)	57	98	36	89	82	0
Min. elevation	274	372	280	366	300	366
Max. elevation	1067	580	1530	1067	1067	1460
Slope (Horton)	*0.26*	*0.35*	*0.49*	0.45	0.46	0.4
Record length (years; start - end dates)	60; 1938 - 1998	60; 1938 - 1998	60; 1938 - 1998	46; 1946 - 1992	51; 1947 - 1998	56; 1942 - 1998
Mean annual precipitation & Std deviation (mm)	1127 ±186 (gauge 11a)	1298 ±223 (gauge 12b)	1319 ± 228 (gauge 13a)		1145 ±207 (gauge 15a)	
Median annual precipitation (mm)	1091.2	1301.7	1295.8		1124.9	
Mean & Std Dev of precipitation in wettest month (mm)	172.5 ± 87.8 July	213.6 ±118.2 June	213 ± 96.6 June		183.6 ±90.2 June	
Mean & Std Dev of precipitation in driest month (mm)	31.9 ±32.2 February	33.8 ±20.3 February	37.9 ±44.3 February		33.6 ±40.4 February	
Mean Annual Runoff & Std deviation: pre-treatment (mm)	245.9 ±220 1938 - 1940	593.6 ±253.6 1938 - 1948	1076.5 ± 367.5 1938 - 1956	564.2 ± 168.5 1946 - 1972	517.8 ±156.7 1947 - 1964	1656.3 ±595.1 1938 - 1992
Mean Annual Runoff & Std deviation: post-treatment (mm)	568.3 ±178 1984 - 1998	416.5 ±162.8 1986-1998	826.5 ±263.6 1958-1998	331.4 ±169.2 1973-1998	509.9 ±155.64 1965-1998	
Mean & Std Dev of *runoff in wettest* month (mm) All data	79 ± 43.6 August	72.8 ±39.8 August	148.7 ±69.7 August	61.5 ±34.3 August	60.1 ±33 August	306.1 ±195 July
Mean & Std Dev of runoff in driest month (mm) All data	13.5 ±4.75 February	10.2 ± 6.1 February	23.8 ± 11.7 February	23 ± 9 February	12 ± 6.2 February	34.8 ±34 February

Study Catchments: Jonkershoek

Bosboukloof	no. 1
Biesievlei	no. 2
Tierkloof	no. 3
Lambrechtsbos A	no. 4
Lambrechtsbos B	no. 5
Langrivier	no. 6

Date taken: 29 March 1938; Scale: approx. 1:30000; Flight/Job no. n/a ; Strip no. n/a; Photo no. Mosaic compiled. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 1 Aerial view of the Jonkershoek catchments in January 1938.

Study Catchments: Jonkershoek

Bosboukloof	no. 1
Biesievlei	no. 2
Tierkloof	no. 3
Lambrechtsbos A	no. 4
Lambrechtsbos B	no. 5
Langrivier	no. 6

Date taken: January 1949; Scale: approx. 1:30000; Flight/Job no. 225; Strip no. 18; Photo no. 03671; Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 2 Aerial view of the Jonkershoek catchments in 1949.

Study Catchments: Jonkershoek

Bosboukloof	no. 1
Biesievlei	no. 2
Tierkloof	no. 3
Lambrechtsbos A	no. 4
Lambrechtsbos B	no. 5
Langrivier	no. 6

Date taken: 1967; Scale: approx. 1:36000; Flight/Job no. 769; Strip no. 19; Photo no. 534; Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 3 Aerial view of the Jonkershoek catchments in 1967.

Study Catchments: Jonkershoek

Bosboukloof	no. 1
Biesievlei	no. 2
Tierkloof	no. 3
Lambrechtsbos A	no. 4
Lambrechtsbos B	no. 5
Langrivier	no. 6

Date taken: 1977; Scale: approx. 1:50000; Flight/Job no. 786; Strip no. 13; Photo no. 1443; Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 4 Aerial view of the Jonkershoek catchments in 1977.

Study Catchments: Jonkershoek

Bosboukloof	no. 1
Biesievlei	no. 2
Tierkloof	no. 3
Lambrechtsbos A	no. 4
Lambrechtsbos B	no. 5
Langrivier	no. 6

Date taken: 1988; Scale: approx. 1:50000; Flight/Job no. 919; Strip no. 13; Photo no. 9381; Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 5 Aerial view of the Jonkershoek catchments in 1988.

2.2.7 Experimental Treatments in Jonkershoek

The five catchments (Map 2) to be treated, namely Bosboukloof, Biesievlei, Tierkloof, Lambrechtsbos B and Lambrechtsbos A, were planted with *Pinus radiata* at approximately eight year intervals. Bosboukloof was afforested to 57% in 1940 (Plate 1). The fynbos in the remaining catchments was protected up to the stage when each was afforested. Langrivier was protected from fire since 1942 and kept as a control catchment.

Biesievlei was afforested to 98% in 1948, Tierkloof to 36% in 1956, Lambrechtsbos B to 82% in 1964, and Lambrechtsbos A to 89% in 1972. In all the afforested catchments except Biesievlei, 20 metre strips (1 chain) were left unplanted either side of streambanks. The natural vegetation in these strips was left intact and allowed to develop (i.e. protected from fire). The rocky cliffs and steeper slopes that form the upper parts of most catchments were also left unafforested. In Tierkloof and Langrivier cliffs comprise large percentages (about 30%) of the total area. In 1961 and 1966 respectively, an additional weir in each of Tierkloof and Langrivier catchments was built in the upper part of the catchments. These were named Waterval (Tierkloof) and Nerine (Langrivier).

2.2.8 Previous analysis of Jonkershoek Experiments

Previous analysis of the primary effects of afforestation or clear felling in the Jonkershoek forestry experiments have been reported by Wicht and Banks (1963), Banks and Kromhout (1963), van Wyk (1977 & 1987), Smith and Scott (1992), Scott (1993 & 1997), Van Wyk and Scott (1993a), Scott *et al.* (1994), and Scott and Smith (1997).

2.3 CATHEDRAL PEAK

2.3.1 History

The Cathedral Peak Forest Influences Research Station was established in1938 as the chief centre for forest hydrological research in the summer rainfall regions, with Mr A.M de Villiers as the research officer (Nänni, 1956). The treatment to be tested were: afforestation with *Pinus patula*, controlled veld burning with and without grazing, and veld protection. This was to complement the hydrological research station already established at Jonkershoek which covered the winter rainfall area.

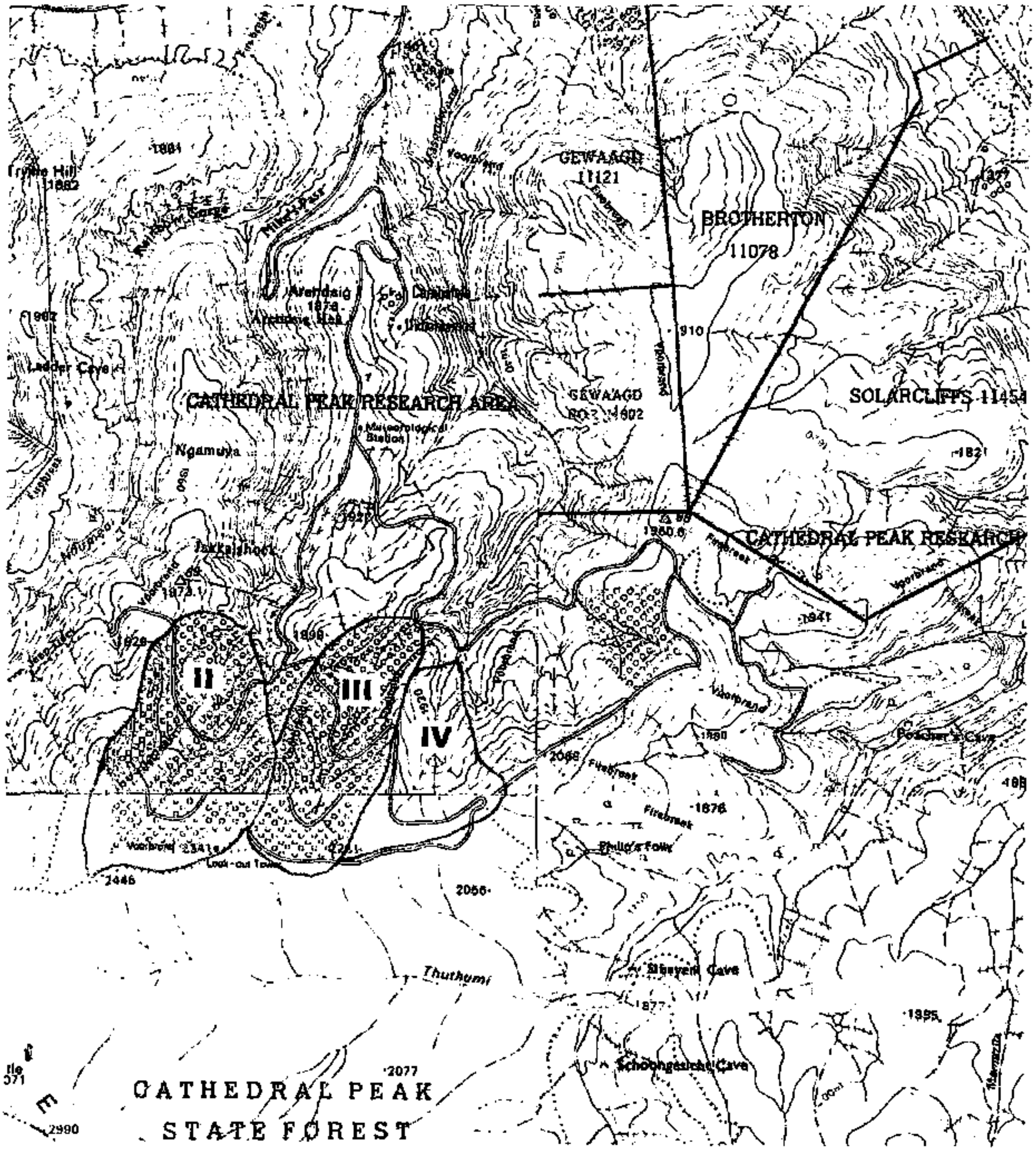
Unfortunately development had to be suspended until 1945 due to the Second World War. Much time was spent in establishing the infrastructure such as building access roads and weirs, siting and erecting of raingauges and weather station. Between 1948 and 1950 measurements at most weirs and raingauges commenced. The physical characteristics of the research catchments used in this study are given in Table 4.

Table 4 The physical characteristics and key variables of the **Cathedral Peak** research catchments used in this study

Variables / Characteristics	**Cath_ii**	**Cath_iii**	**Cath_iv**
Area (ha)	190	138.9	94.7
Percentage afforestation (%)	75	86	0
Min. elevation	1845	1845	1845
Max. elevation	2454	2317	2226
Slope (B - Horton)	0.45	0.38	0.35
Record length (years; start - end dates)	44; 1949 - 1993	35; 1952 - 1991	44; 1949 - 1993
Mean Annual Precipitation & Std deviation (mm)	1431 ±334 (gauge R2)		
Median annual precipitation (mm)	1398.8		
Mean &Std Dev of precipitation in wettest month (mm)	239.4 ±96.6 February		
Mean &Std Dev of precipitation in driest month (mm)	11.4 ±16.7 July		
Mean Annual Runoff & Std deviation: pre-treatment (mm)	806.9 ±191.4 1949 - 1952	683.3 ±383 1951 - 1960	672.7 ±272.2 1949 - 1993
Mean Annual Runoff & Std deviation: post-treatment (mm)	527.1 ±291.3 1953 - 1993	518.2 ±242.4 1961-1981	
Mean &Std Dev of runoff in wettest month (mm) All data	126.8± 84.8 March	116.1 ±90.7 February	137.5 ±76 March
Mean &Std Dev of runoff in driest month (mm) All data	10.3 ±6.5 September	12.2 ±7.5 September	16.4 ± 9.8 September

2.3.2 Location

The Cathedral Peak catchments lie on the Little Berg, below the Drakensberg escarpment bordering the north-eastern side of Lesotho. The area is 42 km west south-west of Winterton (Bergville district), in the Province of KwaZulu-Natal (29°00'S;29°15'E). The Little Berg is a plateau below the basaltic cliffs of the main Natal Drakensberg range that is dissected by deep ravines. Cathedral Peak lies on the base of one of these isolated spurs. There are 15 gauged catchments but data from only three (Catchments II, III, and IV) are used in this study (See Map 3). These three catchments are generally north-facing and the altitudinal range is between 1845 m a.m.s.l. and 2454 m a.m.s.l. The slopes range from almost level at the base to about 40° at the summit.



Study Catchments: Cathedral Peak

Catchment II
Catchment III
Catchment IV

Map ID and source: 2829CC, 1986; 2829CD, 1986; 2929AA, 1982; 2929AB, 1978: Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010
Scale : 1 : 50000

Map 3 Location and topography of the Cathedral Peak study catchments.

2.3.3 Geology and soils

All the research catchments are composed of the Drakensberg Basalt Group (early Jurassic ± 180 Ma). It unconformly overlies the Clarens Formation Sandstone - of Late Triassic age, but the latter is never exposed in the catchment area (Nänni, 1956; SACS, 1980). Two types of lava flow, amygdaloidal basalt and non-amygdaloidal basalt, occur in the research area. The first weathers more rapidly. Three post-Karoo dolerites dykes, each 3 m wide, cut across the research area, but according to (Nänni, 1956) they apparently exert no hydrological influence. One dyke cuts across the lower section of Catchment II, while the other two, about 460 m apart, cross Catchments II, IV, V, VI and X, and Catchments III and IV respectively, both crossing the first one to the NE side of Catchment II. All streams are perennial and rise above apparently solid basalt. The amygdaloidal basalt is probably aquiferous. An erosion feature is the terraces on the steeper slopes, with an average length of 6m and vertical steps of 0.46 m. Individual catchments are well-defined and appear to be "watertight" (Nänni, 1956). However, analysis of the hydrological data (Bosch, 1979) strongly suggests that catchments IV and V are not hydrologically separated; their annual water balance only agrees with those of the other catchments if their data are pooled.

All soils are only moderately weathered, immature soils. All profiles are at least 1.5 m deep, with horizons not well-defined: I = 16 cm dark brown loam permeated with grass roots; II = 31 cm reddish-brown crumbly to granular clay loam (fair expansion/contraction); III = 31 - 46 cm, similar to II but contains rock fragments, often much-weathered. Soil pH is 5,5 in surface horizon and 6.6 in partly decomposed rock. Hutton and Griffin soil forms are most common (Granger, 1976 and Bosch, 1979) and associated with the gentler slopes. Hydrologically the soil profiles appear to be much deeper than described for the agricultural classification, and Everson *et al* (1998) provides more detail on the hydrological depth and functioning of the soil profiles.

2.3.4 Climate

The winters at Cathedral Peak are cold and dry, while the summers are hot and wet (Wicht, 1967). Bosch (1979) provides a fairly detailed description of the weather in the catchments. There were two meteorological stations in the area, one situated just below the catchments on the Little Berg (1830 m a.m.s.l.), while the other one was situated below the Little Berg near the office (1372 m a.m.s.l.). The weather station on the Little Berg was active between 1948 and 1995, whilst the one at the office started in 1952 and is still being maintained the KwaZulu-Natal Nature Conservation Service. The station on the Little Berg measured temperature, relative humidity, sunshine hours, A-pan and S-tank evaporation, wind speed and direction, and rainfall, while the one near the office measures temperature, relative humidity, A-pan evaporation, and rainfall.

2.3.5 Rainfall

Cathedral Peak falls within the summer rainfall region, with 85% of the rain falling in the months October to March inclusive. About 50% of the rain is in the from thunderstorms. Some periods of softer soaking rains may set in for several days. These orographic rains are driven inland from an easterly direction (Nänni, 1956). Occasional snowfalls occur in winter, mostly on the upper parts of the catchments. The mean annual precipitation (MAP) is 1400 mm (Bosch, 1979).

2.3.6 Vegetation

The greatest part of the research catchments is a grassland dominated by *Themeda triandra* [Highland Sourveld (Acocks, 1975) or *T.triandra* sub-alpine grassland (Killick, 1963)]. Of the associated grasses *Tristachya hispida, Trachypogon capensis, Harpechloa capensis, Alloteropsis semialata, Bracharia serrata* and *Monocymbium ceresiiforme* are important as they are adapted to fire. The Protea Open Woodland community is well-developed in the grasslands of the Little Berg, but in the research catchments it only occurs in a small area. In *T. triandra* veld, bracken becomes prominent and forms dense consocies which are seral to fynbos. Woody communities occur in narrow zones along streams, pre-dominated by *Leucosidea sericea* Eckl. & Zeyh. and *Buddleia salviifolia* Lam. *(Granger, 1976 and Bosch, 1979).*

2.3.7 Experimental Treatments in Cathedral Peak

The catchments at Cathedral Peak were set up to test the effects of controlled veld burning with and without grazing, afforestation of grassland with *Pinus patula*, and total protection from fire on streamflow. The treatments were designed to supply information for the refinement of the policy of afforestation in marginal areas and for planning and management of grassland mountain catchments in South Africa (Nänni,1956).

After a controlled burning of Catchment II in 1949, afforestation with *P. patula* started in 1951, leaving an unplanted 20 m strip of riparian zone on either side of the stream. Afforestation was not done all at once as can be seen in Plate 6 (taken in1962). By 1965 all the internal fire breaks were also planted up (Plate 7, taken in 1976). In total the plantation covered 140 ha (74%) of the 190 ha catchment (Bosch, 1980). The bulk of the catchment (36%) however, was afforested in 1951. In Catchment III, 115 ha of the 142 ha was planted with *P. patula* during 1958/59. In 1963 a wildfire destroyed about 41 ha (34%) of the plantation but the area was replanted immediately. Due to wild fires, and the silvicultural practices (pruning and thinning for saw log production) being behind schedule (only one thinning took place before clearfelling) the stands in both catchments were abnormally dense (Bosch, 1980). Between 1971 and 1976 infestation by the Pine brown-tail moth (*Euproctis terminalis*) led to defoliation of about 25% of the trees in each catchment.

In March 1972 it was decided that the original research questions regarding the influence of exotic afforestation on streamflow had largely been answered and that the application of different burning management treatments would be applied to all catchments (Schulze, 1985). No further afforestation would take place. Catchment II was clearfelled between 1981 and 1984 and allowed to rehabilitate to *Eragrostis curvula*. In 1988 all pine regrowth was debarked and left to die off after which a controlled fire was used to reduce the fuel load.

A wildfire in 1981 year killed off all trees in Catchment III, causing heavy silting in the stilling pond after each rain storm (Van Wyk, 1985). This catchment was then also allowed to re-vegetate to *Eragrostis curvula* and in1987 a controlled burn was carried out to reduce the fuel load.

Study Catchments: Cathedral Peak

Catchment II
Catchment III
Catchment IV
Date taken:1962; Scale : approx. 1:30000; Flight/Job no. 477; Strip no. 6; Photo no. 6436. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 6 Aerial view of the Cathedral Peak catchments in 1962.

Study Catchments: Cathedral Peak

Catchment II
Catchment III
Catchment IV

Date taken: 1976; Scale : approx.1:30000; Flight/Job no. 756; Strip no. 23; Photo no. 4738. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 7 Aerial view of the Cathedral Peak catchments in 1976.

2.3.8 Previous analysis of the Cathedral Peak Experiment

Previous analysis of the effects of the two afforestation experiments on total or low flow at Cathedral Peak have been performed and reported by Nänni (1970a), Bosch (1979 & 1980), Smith and Scott (1992), and Scott and Smith (1997).

2.4 WITKLIP

2.4.1 History

Afforestation of the Witklip area started in early 1940's when the grassland was planted with pines, while eucalypts were planted as firebreaks. The objective was to manage the plantations for sawlog production. Trees were planted up to a chain width (20 m) away from stream courses, and 90 m away from vlei and marshy areas. The Witklip dam was built in the 1960's to supply water to the Sandriver irrigation scheme down stream (Wicht and Kluge, 1976). The Witklip experiment site falls within the catchment area of the Witklip dam, and was established in 1975.

2.4.2 Location

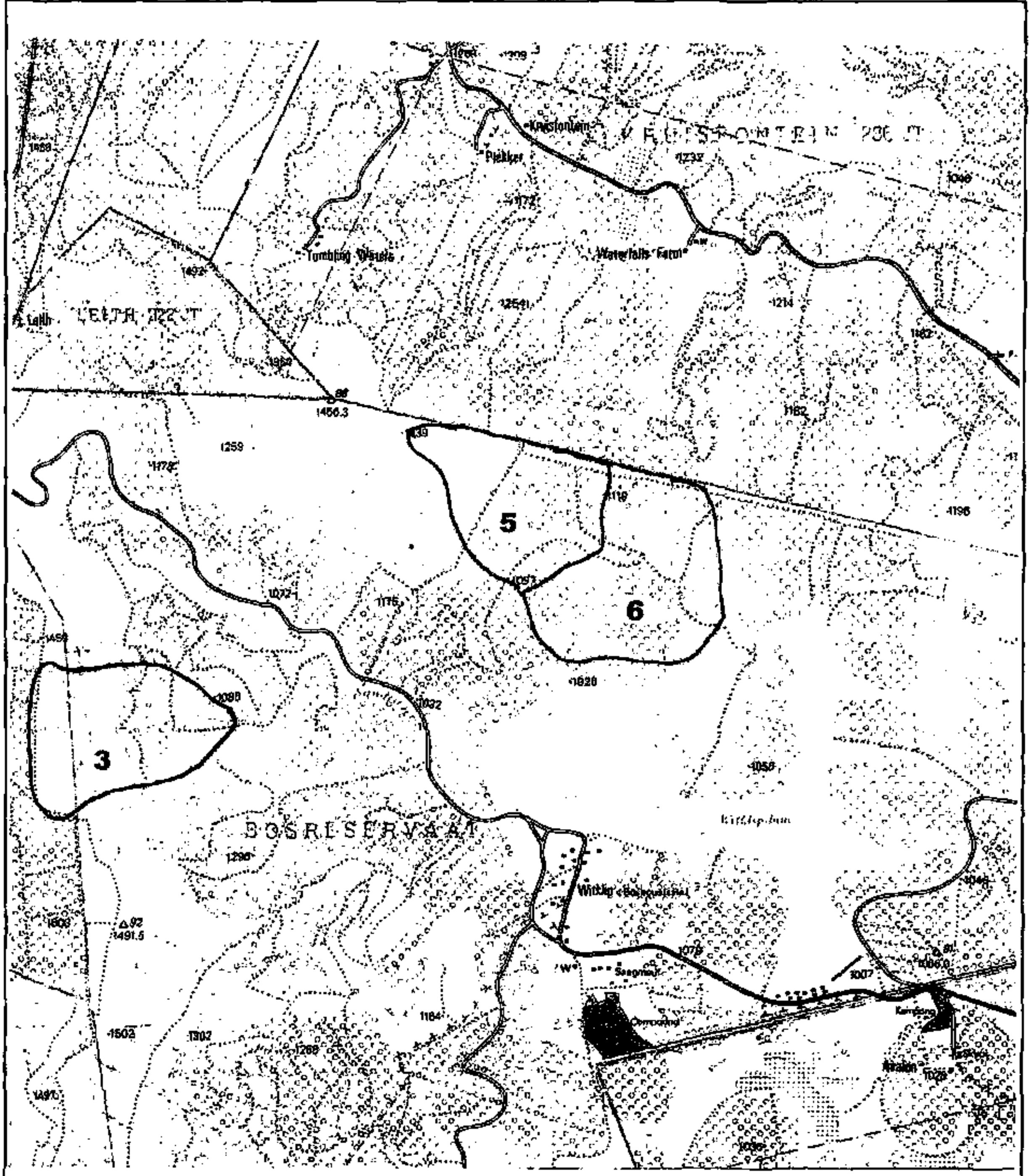
The Witklip catchment experiment was laid out in the Witklip Forestry Station close to the town of White River, Mpumalanga Province (25°14'S; 30°53'E). These catchments form part of the Eastern Drakensberg escarpment and are tributaries of the Witklip river, which in turn flows into the Crocodile river. Catchments 1 to 4 lie adjacent to each other, 5 and 6 form a nested pair and 7 and 8 lie adjacent each other.

The mean altitude is between 1 000 m - 1 470 m a.m.s.l. The catchments used in this study, namely Catchments 5 and 6 both have a north-westerly aspect, whereas Catchment 3, which is used as a control, has an easterly aspect (see Map 4).

2.4.3 Geology and Soils

The upper reaches of the catchments are a plateau and steeply sloping scarp formed from Black Reef Quartzite of early Proterozoic age, Transvaal Sequence (SACS, 1980). These are underlain by the porphyritic Nelspruit granites of Archean age (SACS, 1980), with alluvial material in the valleys.

The soils are mainly formed on deeply weathered granites, and are highly leached and well-drained. Soil types are typically of the Hutton and Clovelly forms in the South African classification (SCWG, 1991). Deep drilling at the nearby Frankfort State Forest that has soils developed in the same deeply weathered granite material, revealed a permeable, stone-free, uniform profile extending down to 38 m below the surface (Dye, 1996). Young eucalypt trees at this specific site were exploiting water in these profiles from below 8 m depths.



Study Catchments: Witklip

Catchment 3
Catchment 5
Catchment 4
Map ID and source: 2530BB, 1986 : Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010.
Scale: 1 : 50000

Map 4 Location and topography of the Witklip study catchments.

2.4.4 Climate

Witklip has a humid sub-tropical climate, with a predominantly summer rainfall. The mean daily temperature in the hottest month (January) is 21.3°C and in the coldest month (July) is 13.4°C (Wicht and Kluge, 1976). There is one weather station next to the forestry office at Witklip plantation where standard air temperature, maximum and minimum temperature, relative humidity, sunshine hours, evaporation, wind speed and wind direction, and rainfall were manually recorded from 25 April 1974 to 21 July 1992. The station was automated in August 1991 and was closed in March 1995.

2.4.5 Rainfall

At Witklip, a network of Casella recording raingauges, each paired with a standard Snowdon with Nipher shield recorded rainfall on a continual basis. Standard Snowdon "B" gauges with Nipher shields were used to measure weekly rainfall. The mean annual precipitation (MAP) for Witklip over the period 1975 to 1990 was 1005 mm. The rainfall and physical characteristics of the catchments are shown in Table 5.

Table 5 The physical characteristics and key variables of the **Witklip** catchments used in this study.

Variables / Characteristics	Witklip_3	Witklip_5	Witklip_6
Area (ha)	160	108	165.3
Percentage afforestation (%)	34	51	82
Min. elevation	1130	1080	1000
Max. elevation	1470	1340	1080
Slope (B - Horton)			
Record length (years; start - end dates)	15; 1975 -1990	15; 1975 - 1990	15; 1975 - 1990
Mean Annual Precipitation & Std deviation (mm)			1005 ±301.1 (gauge R6)
Median annual precipitation (mm)			1090.8
Mean &Std Dev of precipitation in wettest month (mm)			190.7 ± 119 February
Mean &Std Dev of precipitation in driest month (mm)			4.98 ± 32.2 July
Mean Annual Runoff & Std deviation: pre-treatment (mm)	362.2 ± 212.8 1975 - 1990	261.7 ±119.6 1975 - 1990	259.7 ±151.8 1975 - 1982
Mean Annual Runoff & Std deviation: post-treatment (mm)			296.9 ± 145.1 1983 - 1990
Mean &Std Dev of runoff in wettest month (mm) All data	71 ±456 February	55.5 ±37.4 February	61.1 ±41.3 February
Mean &Std Dev of runoff in driest month (mm) All data	16.7 ±5.4 August	9.15 ±6.8 October	10.22 ±10.2 September

2.4.6 Vegetation

The indigenous vegetation is montane grassland, with evergreen forest developing in the sheltered valleys and gallery forest on the escarpment, grading into riparian scrub at higher altitudes. Plates 8 and 9, which were taken in 1939 when afforestation had not yet started, clearly shows the vast areas of montane grassland in the Witklip area.

2.4.7 Experimental Treatments in Witklip

The main purpose of the research infrastructure at Witklip was to measure the effects of treating riparian zones on streamflow components at a catchment scale. The problem with the research layout was that no good control catchment could be established since all catchments experienced some silvicultural activity, which meant there was no catchment with a long-term stable plant cover. As a result, experiments are confined to relatively short comparisons. Catchments 5 and 6 are of the nested type, with 5 the upper gauge and 6 lower down in the same catchment. Catchment 5, with a total area of 108 ha, was to serve as a control for Catchment 6 (165.3 ha). With the current analysis, however, Catchment 3 was used as a control for both Catchments 5 and 6, as both had clearfelling treatments.

Afforestation of Catchment 5 took place during 1942/44, and again in 1955/56. This covered 52% (56.3 ha) of the catchment, leaving the upper part (51.7 ha) under indigenous vegetation (grasslands on the slope and indigenous scrub in the riparian zones). Of the area under afforestation, 46.8 ha was planted with *Pinus patula* and *P. roxburghii*, while the other 9.5 ha was fire belts, planted with *Eucalyptus saligna* and *E. paniculata*. Clearfelling took place between June 1980 and June 1983. The area was then progressively re-planted.

Afforestation of Catchment 6 took place between 1940 and 1944, leaving a 20 m wide riparian strip on either side of streams. Plates 10 and 11, taken in 1954, show Catchment 3, and Catchments 5 and 6, respectively, when the trees were between 9 and 13 years old. The area under plantation including fire belts was approximately 122 ha (74%) of the total catchment. The clearfelling treatment (100% clearing) took place between 1978 and 1982. Plate 12 shows the area as they were in 1981, after clearfelling had started in Catchments 5 and 6. Plate 13 show Catchments 5 and 6 in 1985 after most clearfelling had taken place. The compartments were re-afforested as clearfelling was completed.

Catchment 3 covers an area of 160 ha, of which 104.8 ha comprises indigenous vegetation and 54.2 ha comprises pine plantation (*Pinus elliottii* and *P. patula*) and eucalyptus fire belts (*E. paniculata, E. maculata, E. albens*). Most compartments were planted in 1948 (Smith, 1991).

2.4.8 Previous Analysis of Clear felling effects at Witklip

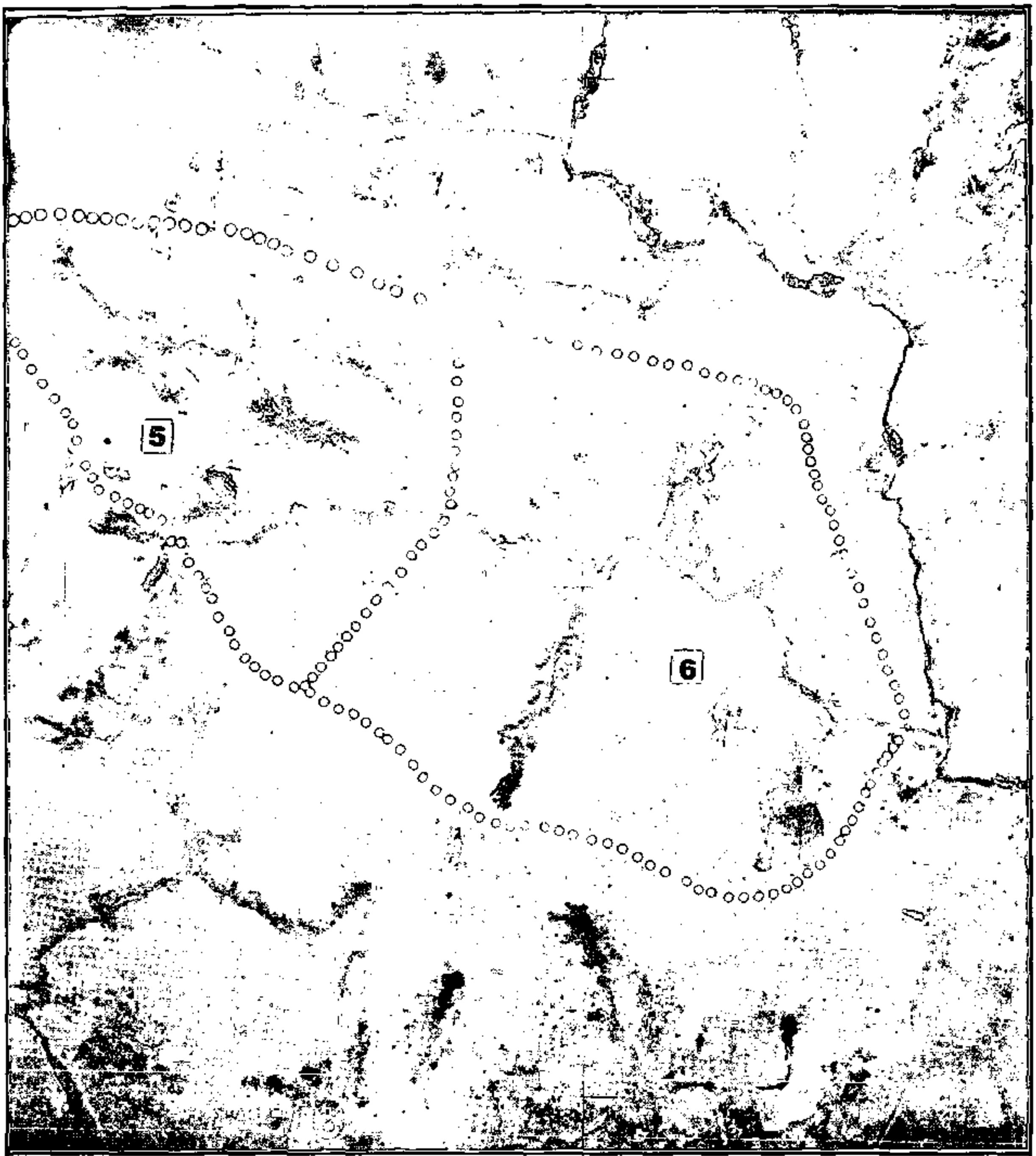
Previous analysis of the effects of clear felling at Witklip were performed for Catchment 5 by Smith (1991) and for Catchment 2 by Van Wyk and Scott (1993b).

Study Catchments: Witklip

Catchment 3

Date taken: 1939; Scale : approx. 1:11000; Flight/Job no. 149; Strip no. n/a; Photo no.28500. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 8 Aerial view of the Witklip catchment 3 in 1939.



Study Catchment: Witklip

Catchment 5
Catchment 6

Date taken: 1939; Scale : approx. 1: 11000; Flight/Job no.149; Strip no. n/a; Photo no.28527. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 9 Aerial view of the Witklip catchments 5 and 6 in 1939.

Study Catchments: Witklip

Catchment 3

Date taken: 1954; Scale : approx.1:30000; Flight/Job no. 325; Strip no. 44; Photo no. 5179. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 10 Aerial view of the Witklip catchment 3 in 1954.

Study Catchments: Witklip

Catchment 5
Catchment 6

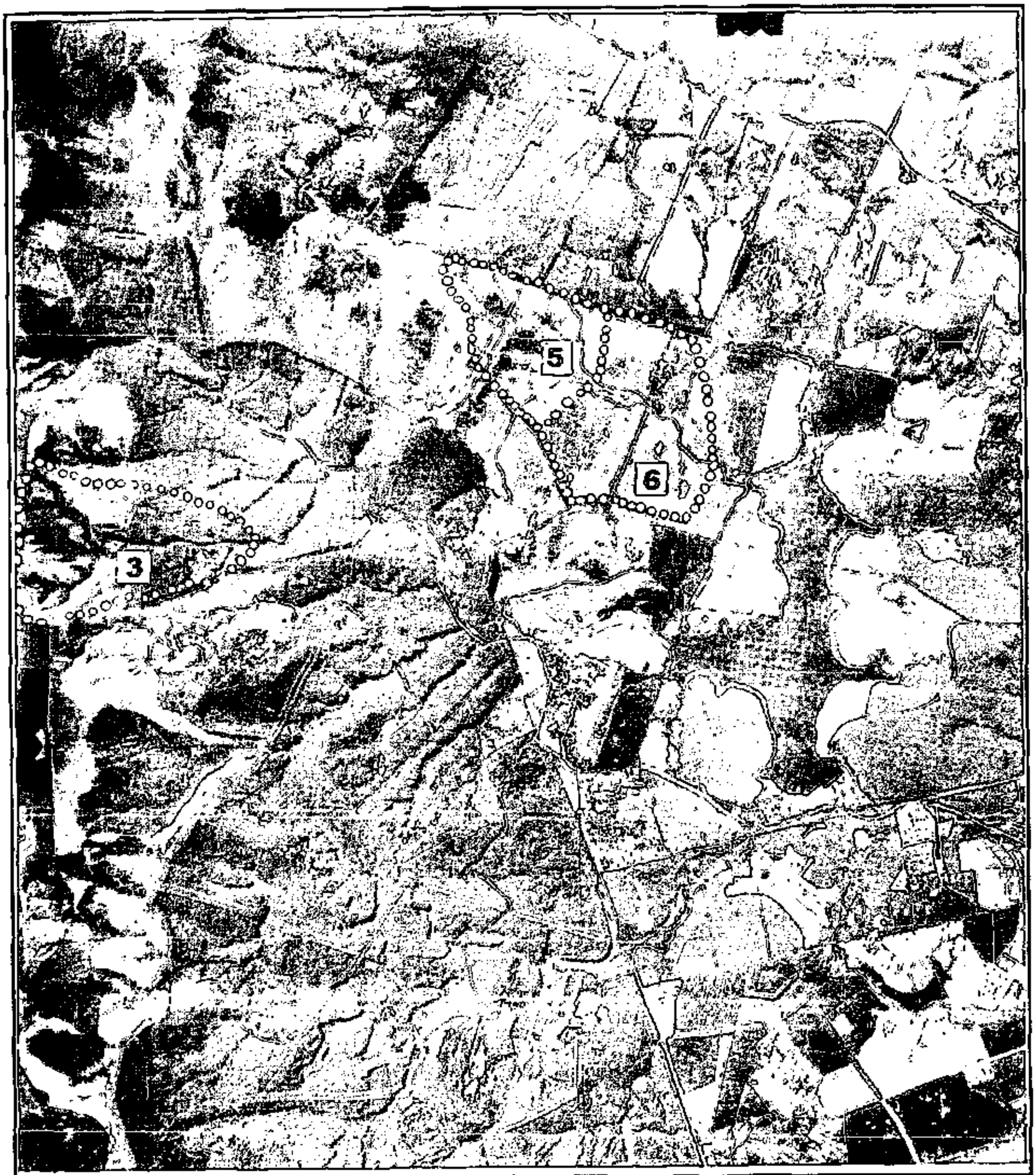
Date taken: 1954; Scale : approx. 1:30000; Flight/Job no.325; Strip no. 44; Photo no.5180. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 11 Aerial view of the Witklip catchments 5 and 6 in 1954.

Study Catchments: Witklip

Catchment 3
Catchment 5
Catchment 6
Date taken: 8 September 1981; Scale : approx. 1:30000; Flight/Job no.848; Strip no. 16; Photo no.6196.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 12 Aerial view of the Witklip catchments in 1981.



Study Catchments: Witklip

Catchment 3
Catchment 5
Catchment 6

Date taken: 25 July 1985; Scale : approx. 1:50000; Flight/Job no.875; Strip no. 12; Photo no.7067.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 13 Aerial view of the Witklip catchments in 1985.

2.5 MOKOBULAAN (UITSOEK STATE FOREST)

2.5.1 History

The Mokobulaan catchment experiment was started on the Mpumalanga escarpment in 1956. Three small catchments were selected, and the rainfall and runoff measured. The aim was to supplement the research experiments that were underway at Jonkershoek and at Cathedral Peak. After a period of calibration two catchments were to be afforested with different species, while the third was to be kept as grassland and grazed by sheep under a conservative regime (grazed for 3 years and rested in the fourth year). The recommended rate of stocking was about seven sheep per hectare. Controlled burning was to be applied during spring in the fourth year (Nänni, 1971). According to Nänni (1971) this ideal treatment could not be maintained.

2.5.2 Location

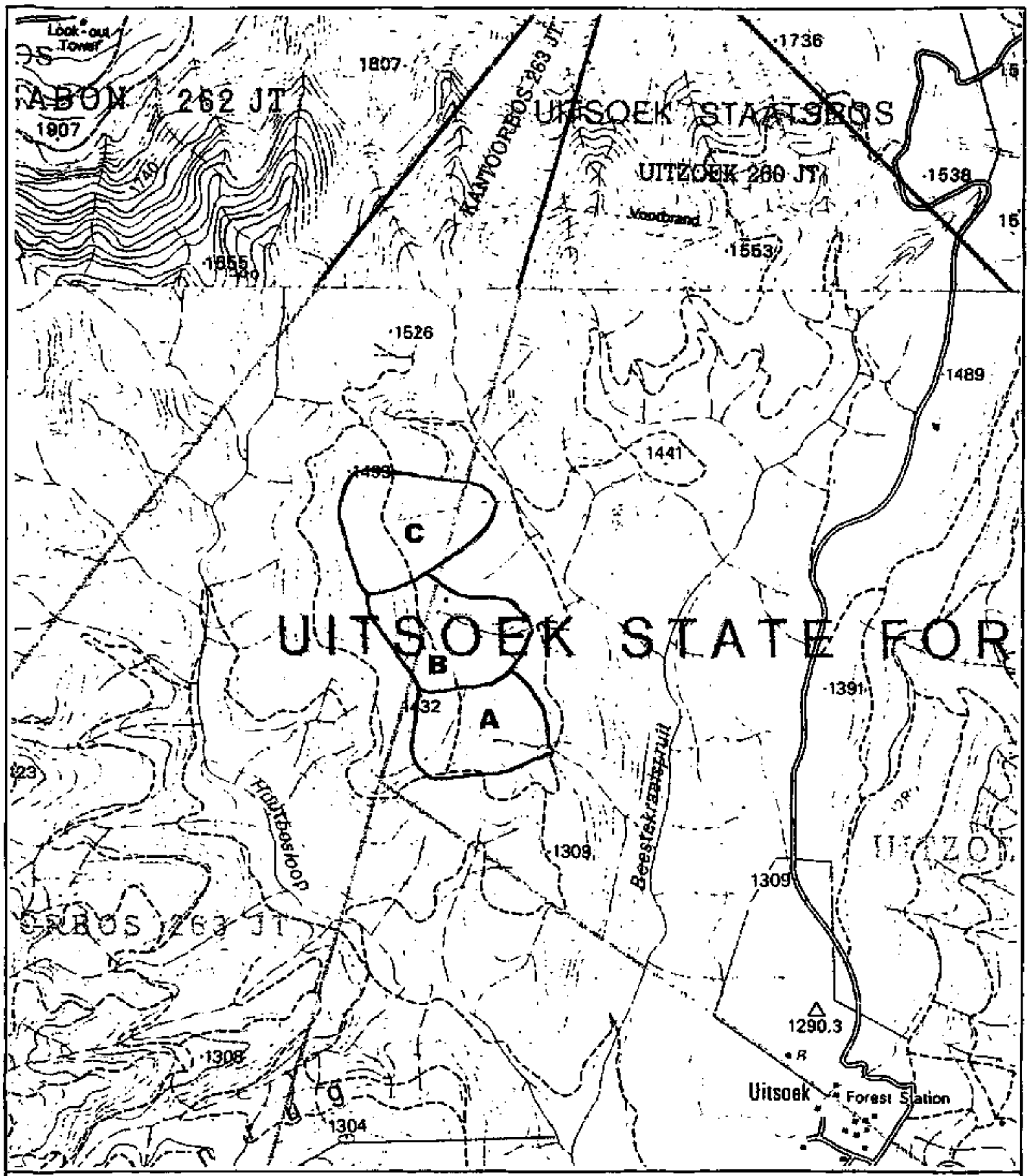
The research area, which is part of Uitsoek Plantation, lies on the Mpumalanga Drakensberg, on a spur isolated by deep gorges at about 1292 to 1494 m a.m.s.l. It is just south-east of Lydenburg (Van Lill *et al.*, 1980), and 48 km west-north-west of Nelspruit, at latitude 25°17'S and longitude 30°34"E. Streams draining the area flow into the Houtboschloop which in turn is a tributary of the Crocodile river. The three catchments A, B and C have an easterly aspect (Map 5).

2.5.3 Geology and Soils

The research area lies on the basal shales of the Daspoort Stage of the Pretoria Group Transvaal Supergroup (Early Proterozoic). The shales are highly arenaceous with many bands of argillaceous, ferrugenous sandstone and quartzite grading into shale. There is no folding in the catchments and all the shale beds dip a gentle 2 - 4° to the west. Seven diabase dykes cross the catchment with a predominant strike of north-east to south east; some occupy fault planes. There is a diabase sill along the top of all three catchments. According to Nänni (1971) the movement of groundwater into or out of the catchments is seen as unlikely - all were thought to be impervious.

The soil of the research area is clayey sand interspersed with deeply weathered shale and sandstone fragments in a thin layer, underlain by soft yellow shale. Some harder sandstones stand out as small ridges. Bedrock is generally broken, semi-weathered, and permeable to roots and water. This is necessary for plant growth as the soil is only a few centimetres deep (Nänni, 1971).

Deep drilling in Mokobulaan revealed that the shales are broken and unsaturated to 30 m below the surface and rooting is thought to be possible for much of this depth (Dye, 1996). Along stream banks there are pockets of deep loam soil (Nänni, 1971).



Study Catchments: Mokobulaan

Catchment A
Catchment B
Catchment C
Map ID and source: 2530BC, 1984; 2530BA, 1988: Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010.

Map 5 Location and topography of the Mokobulaan study catchments.

2.5.4 Climate

Mokobulaan experiences cold, dry winters and hot, wet summers and falls within Köppen's (1931) class Cwb, according to Wicht (1967). Maximum temperatures rarely exceed 38°C. The mean annual evaporation from an A-pan at the nearby Uitsoek station is 1723 mm (Midgley *et al.*, 1994). Sometimes strong winds of short duration are experienced. In 1985 an automated weather station was erected in catchment C, bordering Catchment B, which measures temperature, relative humidity, solar radiation, wind speed, wind direction and rainfall.

2.5.5 Rainfall

The mean annual precipitation (MAP) for Mokobulaan is 1180 mm (Table 6) of which 82% falls in the summer months (Oct-March). Both orographic and convectional storms bring rain. Other forms of precipitation are hail and mist, but these are negligible. There are two Snowdon raingauges fitted with Nipher shields per catchment - a lower (near weir) and upper. Two recording gauges in Catchment B provide continuous records of rainfall.

Table 6 The physical characteristics and key variables of the Mokobulaan research catchments used in this study.

Variables / Characteristics	Mokobulaan A	Mokobulaan B	Mokobulaan C
Area (ha)	26.2	34.6	36.9
Percentage afforestation (%)	~97	~95	0
Min. elevation	1292	1318	1341
Max. elevation	1433	1486	1494
Slope (B - Horton)	0.23	0.22	0.26
Record length (years; start - end dates)	35;1957-1990	35;1957-1990	35;1957-1990
Mean Annual Precipitation & Std deviation (mm)	1166 ± 185	1180 ± 179	1199 ± 184
Median annual precipitation (mm)	1189	1197	1167
Mean &Std Dev of precipitation in wettest month (mm)	159 ± 85.5 * February		
Mean &Std Dev of precipitation in driest month (mm)	10.9 ± 19.1 * June		
Mean Annual Runoff & Std deviation: pre-treatment (mm)	197 ± 135.1 1956 - 1968	195.8 ± 93.2 1956 - 1971	117.9 ± 97.9 1957 - 1998
Mean Annual Runoff & Std deviation: post-treatment (mm)	36.5 ± 67.4 1970 - 1998	167.6 ± 144.5 1972 - 1982	
Mean &Std Dev of runoff in wettest month (mm) All data	15.3 ± 20.87 March	31.1 ± 22.6 February	25.2 ± 24.7 February
Mean &Std Dev of runoff in driest month (mm) All data	2.55 ± 5.35 October	8.6 ± 5.9 October	2.6 ± 2.6 September

* **Uitsoek Weather Station**

2.5.6 Vegetation

The Mokobulaan research area was almost entirely grassland. Although the vegetation falls within the North-Eastern Mountain Sourveld (Acocks, 1975) it has some affinity with the Lowveld Sour Bushveld which is drier and occurs at lower elevations. The climax grass cover should be *Themeda triandra* but the inferior grazing grass *Aristida junciformis* dominates because of incorrect management in the past (Nänni, 1971). The grass height on average is 45 cm, while the riverine forest, about 12 m high, occurs along the more protected streams. Plate 14, dating from 1936, shows the typical grass cover, with the narrow (20 m wide) strips of riverine forest along the streams that occurred there during the past century. In Catchment B the riverine forest is almost non-existent except for a small patch higher up along the stream in the middle of the catchment. In Plate 15 (taken in 1964), the riverine strips seem more developed, perhaps due to carefully controlled burning operations. Currently the riverine forest is a mixture of evergreen broadleaf species with no particular species dominating. Some lianas and a few deciduous species also occur.

2.5.7 Experimental Treatments in Mokobulaan

The paired catchment experiment at Mokobulaan was set up to measure the effect of afforestation with *Eucalyptus grandis* and *Pinus patula* on streamflow components relative to rotationally burned and grazed North-Eastern Mountain Sourveld. Complete afforestation, including riparian zones, was to be carried out in both treatment catchments (Nänni, 1971).

After an initial calibration period (1957 to 1969), catchment A, with an area of 26,2 ha, was 100% afforested in February 1969 with *Eucalyptus grandis* (Van Lill, *et al.*, 1980). Following a pre-treatment (calibration) period of 1957 to 1970, the entire 34.6 ha of Catchment B, was afforested in January 1971 with *Pinus patula*. The third catchment (C; 36.9 ha) was kept as grassland control and, conservatively, burnt and grazed with sheep. The grazing was discontinued in 1971, whereafter biennial winter burning, weather permitting, was carried out.

It can be seen in Plate 16 (taken in September 1981) that afforestation did not take place in the riverine areas, as there is a distinct separation between the riverine forest and the plantation. Plate 17, taken in 1988, confirms this.

2.5.8 Previous Analysis of the Mokobulaan Catchments

Previous analyses of the primary effects of afforestation or clear felling in the two Mokobulaan experiments have been performed and reported by Van Lill *et al.* (1980), Smith and Scott (1992), Scott and Smith (1997), and Scott and Lesch (1997).

Study Catchments: Mokobulaan (Uitsoek)

Catchment A
Catchment B
Catchment C

Date taken: 15 May 1936; Scale : approx. 1:11000; Flight/Job no. 110; Strip no. - ; Photo no. 27223.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 14 Aerial view of the Mokobulaan (Uitsoek) catchments in 1936.

Study Catchments: Mokobulaan (Uitsoek)

Catchment A
Catchment B
Catchment C

Date taken: 24 May 1964; Scale : approx. 1:50000; Flight/Job no. 481; Strip no. 5; Photo no. 065. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 15 Aerial view of the Mokobulaan (Uitsoek) catchments in 1964.

Study Catchments: Mokobulaan (Uitsoek)

Catchment A
Catchment B
Catchment C

Date taken: 8 September 1981; Scale : approx. 1:30000; Flight/Job no. 848; Strip no. 17; Photo no. 6251.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 16 Aerial view of the Mokobulaan (Uitsoek) catchments in 1981.

Study Catchments: Mokobulaan (Uitsoek)

Catchment A
Catchment B
Catchment C

Date taken: 1985; Scale : approx. 1:30000; Flight/Job no. 875; Strip no. 8; Photo no. 4099. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 17 Aerial view of the Mokobulaan (Uitsoek) catchments in 1985.

2.6 WESTFALIA

2.6.1 History

The first plantations of *Eucalyptus grandis* on the Westfalia Estate, near Tzaneen in the Northern Province, were established in 1931. Water supplies began to dwindle and Dr Hans Merensky, the then Director of the Estate, suspected the eucalypts to be the cause. He therefore had the catchments cleared and re-established indigenous vegetation, also allowing natural bush to return. This appeared to result in a considerable increase in streamflow (Smith and Bosch, 1989). These experiments however were not set up under controlled conditions, so the results were inconclusive. In the early seventies the Department of Forestry, in collaboration with the Hans Merensky Foundation, decided to set up a carefully controlled multiple catchment experiment on the Westfalia Estate. Plate 18, taken in 1938, shows the proposed experimental area as still being under grassland, with only the riparian areas covered with indigenous bush.

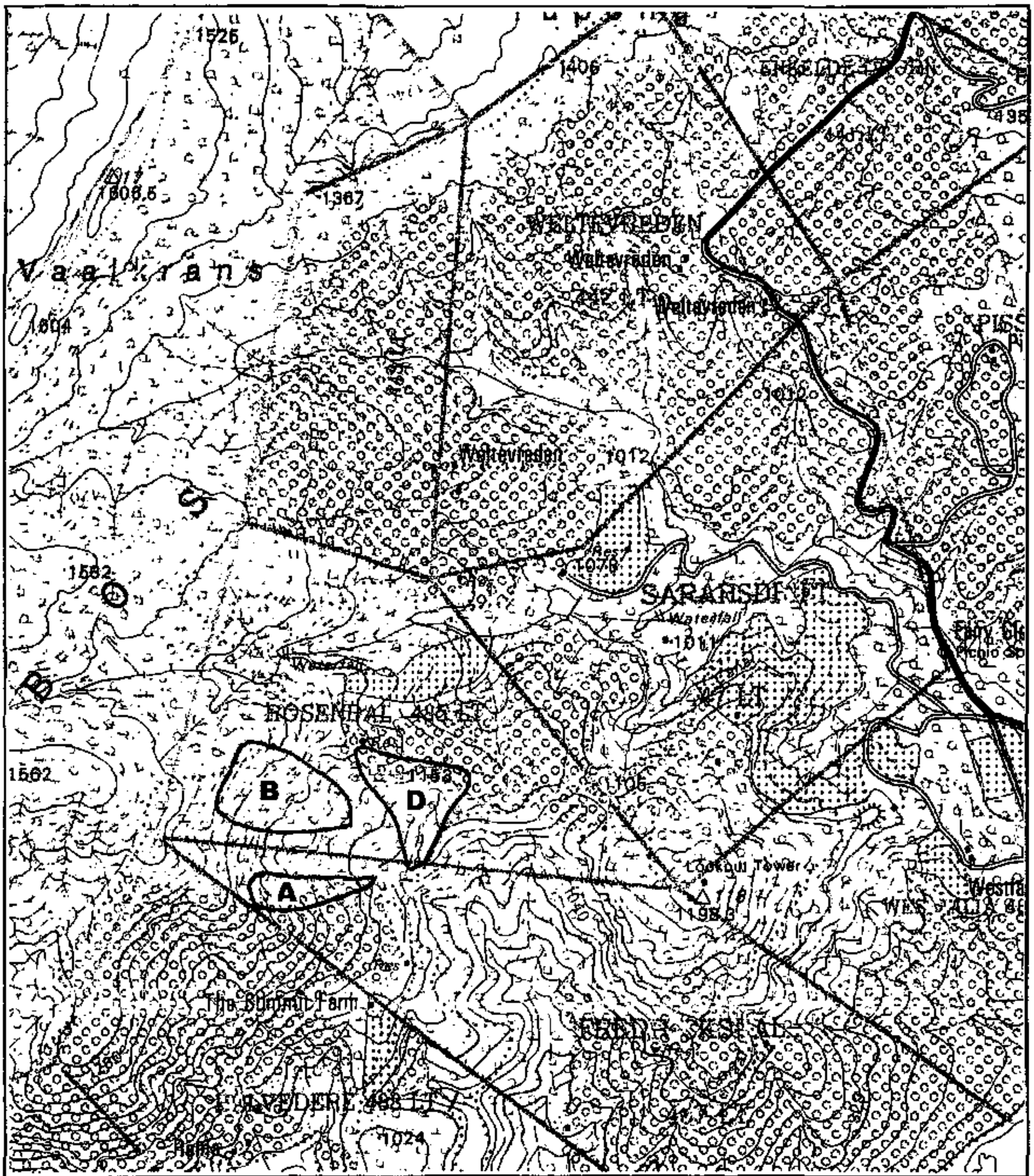
2.6.2 Location

The paired catchment experiment is situated on the Westfalia Estate, some 13 km southwest of Duiwelskloof, and northwest of Tzaneen, on the slopes of the Great Eastern Escarpment of South Africa (23°44'S; 30°04'E). The research area consists of four catchments namely A, B, C and D, of which C has since been closed. Only Catchments A, B and D are reported on. The altitude of catchments A, B and D range between 1 050 and 1 400 m a.m.s.l. Both Catchments B and D have a south-eastern aspect, while A has an north-easterly aspect. The streams are tributaries of the Madikeleni stream, which in turn flows into the Great Letaba River (Map 6).

2.6.3 Geology and Soils

The bedrock underlying these catchments is a biotite-bearing Archean granite gneiss (Nelspruit type) with diabase dykes and sills criss-crossing the area with some intrusions of Turfloop granite (Döhne, 1984). The base on which this lies is the Mothiba form of the Pietersburg group, which is of the ultramafic and mafic metavolcanics types, and includes serpentinite and shist. Some quartzite fraction is present, together with some banded ironstone.

Most of the soils are well-drained, deep red soils of the Hutton, Farningham and Balmoral series of the Hutton form (according to the South African binomial soil classification of Macvicar *et al.*, 1977). A minor part of the cooler slopes have deeper A-horizons on soils which classify as Inanda (Döhne, 1984). The clay content of these dominant soils is between 20 and 60%, and the dominant clay mineral is the weakly expansive kaolinite (Döhne, 1984). The soils are therefore stable with low erodibility characteristics, and a high permeability. The lower third of the riparian zone in Catchment D has hydromorphic soils, with a deep organic horizon overlying gleyed material (Champagne series of the Champagne form, Macvicar *et al.*, 1977). This soil indicates shallow saturation levels and a horizon with a considerable capacity to trap sediment from higher slopes. The humic and organic topsoils are vulnerable to erosion if exposed and cultivated.



Study Catchments: Westfalia

Catchment A
Catchment B
Catchment D

Map ID and source: 2330CA, 1983: Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010

Map 6 Location and topography of the Westfalia study catchments.

Study Catchments: Westfalia

Catchment A
Catchment B
Catchment D

Date taken: 11 July 1938; Scale : approx. 1:13000; Flight/Job no. 131; Strip no. 38; Photo no. 56702.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 18 Aerial view of the Westfalia catchments in 1938.

2.6.4 Climate

The climate at Westfalia is subtropical with a summer rainfall season. Monthly mean daily maximum temperature is between 21 and 30°C. Monthly mean daily minimum temperatures vary between 2°C and 10°C (Bosch and Smith, 1989).

2.6.5 Rainfall

The mean annual precipitation of the Westfalia catchments was 1253 mm (over the period 1975 to 1998, Table 7). At Tzaneen, which is 16% drier over a comparable period of record, the mean annual precipitation between 1915 and 1994 was 1245 mm. Almost 84% of rain falls during the summer months (October - March). The rainfall is mainly orographic, typified by a soft drizzle. Convective thunderstorms are common early in the rainy season. Wind occurs less frequently towards mid-summer (Scheepers, 1966).

Table 7 The physical characteristics and key variables of the Westfalia research catchments used in this study.

Variables / Characteristics	Westfalia B	Westfalia D
Area (ha)	32.6	39.6
Percentage afforestation (%)	0	83
Min. elevation	1140	1050
Max. elevation	1420	1320
Slope (B - Horton)	0.42	0.33
Record length (years; start - end dates)	23;1975-1998	23;1975-1998
Mean Annual Precipitation & Std deviation (mm)		1253 ±480.7 (gauge R3)
Median annual precipitation (mm)		1181.8
Mean &Std Dev of precipitation in wettest month (mm)		246 ±142.8 February
Mean &Std Dev of precipitation in driest month (mm)		16.9 ±34.8 July
Mean Annual Runoff & Std deviation: pre-treatment (mm)	492.3 ±387 1975 - 1998	590.5 ±341.1 1975 - 1981
Mean Annual Runoff & Std deviation: post-treatment (mm)		190.5 ± 203.9 1983 - 1998
Mean &Std Dev of runoff in wettest month (mm) All data	111.5 ±102.5 February	55.6 ±63.2 February
Mean &Std Dev of runoff in driest month (mm) All data	15.1 ±11.1 October	13.1 ±13.7 September

2.6.6 Vegetation

The natural vegetation of the Westfalia catchments is transitional between Acocks' (1975) North Eastern Mountain Sourveld (evergreen high forest) and Lowveld Sour Bushveld (deciduous woodland). The mainly mixed scrub forest and closed canopy forest of Catchment B (and D before treatment) had a mean tree height of 10 m, with dominant species such as *Syzygium cordatum* (Myrtaceae), *Nuxia floribunda* (Loganiaceae), *Rapanea melanophloeos* (Myrsinaceae) and *Trimeria grandiflora* (Flacourtiaceae). The mean tree trunk diameter at breast height was 100 mm (Bosch and Versfeld, 1984).

2.6.7 Experimental Treatments in Westfalia

This paired catchment experiment was initiated to test the effect of removal of indigenous riparian vegetation on streamflow, and the replacement of indigenous vegetation with exotic timber species. The re-growth of indigenous vegetation and the exclusion of fire in Catchment B (32.6 ha) and Catchment D (39.6 ha) allowed indigenous bush to return (Bosch and Smith, 1989). Plate 19, taken in 1977 before treatment, shows Catchment D completely covered with indigenous bush. As part of the experimental treatment, the riparian vegetation in Catchment D (10% of the total catchment area) was cut in February 1981 and left on the ground. The rest of the indigenous forest in Catchment D (83% of the total catchment area; the balance of the area was existing eucalypt plantation) was then cleared (bulldozed) completely in December 1982, the material stacked and burnt. In March 1983, the cleared area was afforested with *Eucalyptus grandis* up to the stream edge (Smith and Bosch, 1989). In 1990, which was the beginning of a very dry 5 year spell, the stream in Catchment D started to dry up.

In 1995 the riparian zone in Catchment D (about 12% of the catchment area) was clearfelled, and the area has been kept clear of regrowth since (see Plate 20). After exceptionally high rainfall during the summer of 1995/96, the stream in Catchment D started flowing again, and has continued to flow since then.

2.6.8 Previous Analyses of the Westfalia Afforestation Experiment

Previous analyses of the primary effects of afforestation or clearfelling in Westfalia D have been performed and reported by Bosch and Smith (1989), Smith and Scott (1992), Scott and Lesch (1996), and Scott and Smith (1997).

Study Catchments: Westfalia

Catchment A
Catchment B
Catchment D

Date taken: 1977; Scale : approx. 1:30000; Flight/Job no. 779; Strip no. 22; Photo no. 9569. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 19 Aerial view of the Westfalia catchments in 1977.

Study Catchments: Westfalia

Catchment A
Catchment B
Catchment D

Date taken: 20 November 1997; Scale : approx. 1:30000; Flight/Job no. 1002; Strip no. 9; Photo no. 9546.
Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 20 Aerial view of the Westfalia catchments in 1997.

2.7 NTABAMHLOPE

2.7.1 History

During the drought of 1932/33 the Government was asked to institute investigations into the problem of conservation of water, soil and vegetation. In 1935 land for an agricultural research station was acquired and large scale soil conservation structures were constructed. The weirs in the Ntabamhlope catchments were only erected in 1962. With the help of the Water Research Commission, gauging of some of the original network of stations was resumed by the Department of Agricultural Engineering of the University of Natal in Pietermaritzburg in the 1980's. More detail on the history of the Ntabamhlope catchments can be found in an excursion guide to the sites (Schulze, 1985).

2.7.2 Location

The Ntabamhlope catchment area is situated on the KwaZulu-Natal midlands (29°04'S; 29°39'E), about 25 km west of Estcourt. The altitude is about 1440 m a.m.s.l. There are a number of catchments but only three are used in this study (see Map 7).

2.7.3 Geology and Soils

The catchment area mostly consists of alternating sandstones and mudstones/shales belonging to the Beaufort Group of the Karoo Supergroup (Schulze, 1985). Sills and dykes of dolerite traverse the catchments.

The soils of Ntabamhlope are highly varied with both mesotrophic and dystrophic types. Schulze (1985) gives a more detailed explanation.

2.7.4 Climate

Ntabamhlope falls in the summer rainfall area, similar to Cathedral Peak with hot, wet summers and cold, dry winters, when frost is experienced frequently. The monthly means of daily maximum temperatures range from 24.5°C for January to 12.9°C for July, whereas the mean daily minimum is 12.9°C for January and -3.3°C for June (Schulze, 1985).

2.7.5 Rainfall

The mean annual precipitation for Ntabamhlope is 1115 mm, following a distinctly seasonal pattern with most rain falling in December and January (Schulze, 1985).

Study Catchments: Ntabamhlope

Catchment V7H003
Catchment V7H004
Catchment V7H008
Map ID and source: 2929BA, 1975 : Chief Director of Surveys and Mapping, Private Bag, Mowbray, 8010.
Scale: 1 : 50000

Map 7 Location and topography of the Ntabamhlope study catchments.

2.7.6 Vegetation

The grassland area surrounding the vlei at Ntabamhlope consists of mostly of *Themeda* and *Hyparrhenia* communities (Chapman, 1990). These grasslands are maintained by controlled burning during the drier months, discouraging the encroachment of scrub. Vegetation in the vlei itself consists of various wetland vegetation types. Chapman (1990) provides more background.

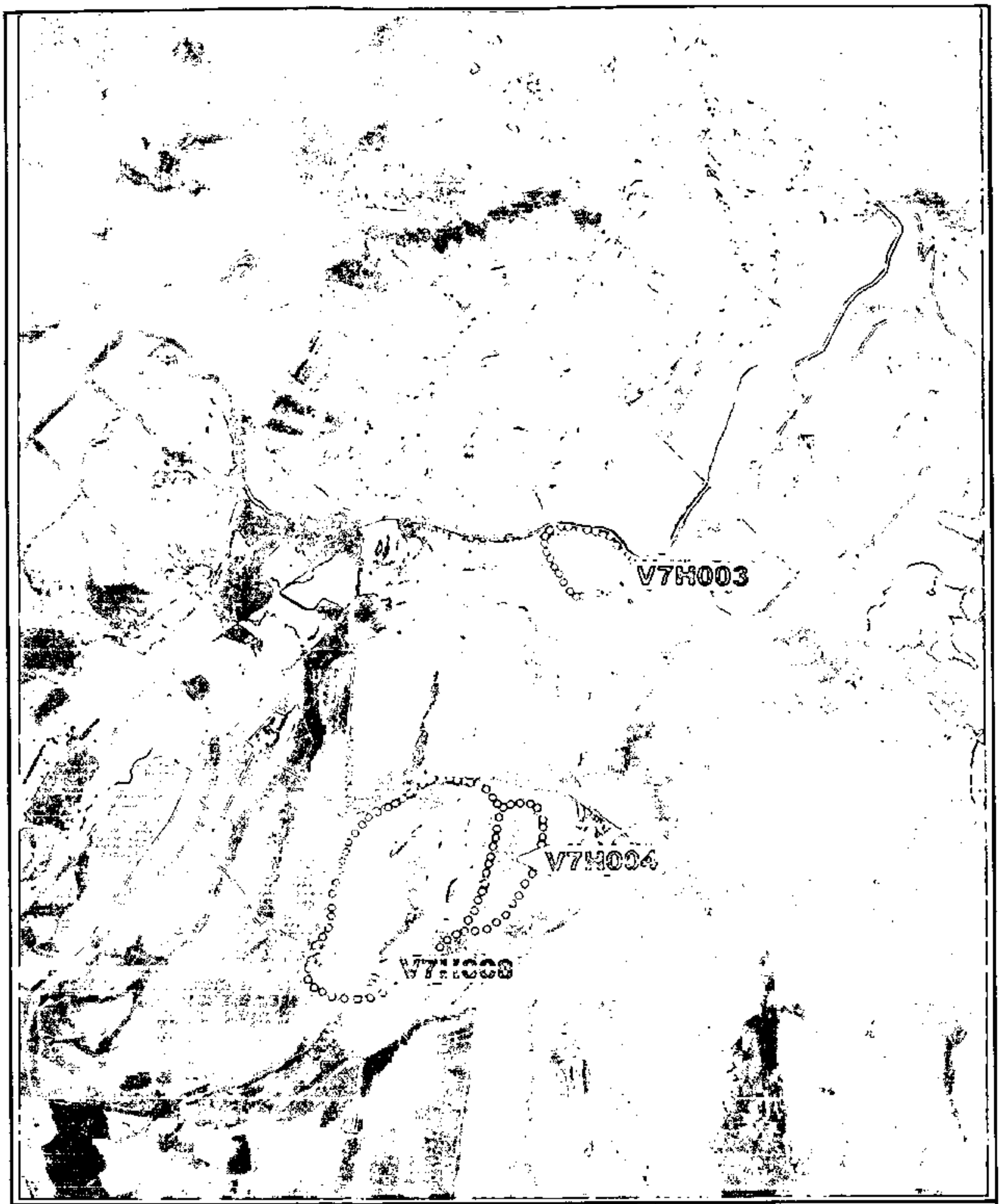
2.7.7 Experimental Treatments in Ntabamhlope

Plate 21 shows the Ntabamhlope catchments in 1964, while Plate 22 is an aerial photo taken in 1992.

Study Catchments: Ntabamhlope

Catchment V7H003
Catchment V7H004 (not visible on photograph)
Catchment V7H008 (not visible on photograph)
Date taken: 13 June 1964; Scale : approx. 1:30000; Flight/Job no. 488B; Strip no. 6; Photo no. 376. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 21 Aerial view of the Ntabamhlope catchments in 1964



Study Catchments: Ntabamhlope

Catchment V7H003
Catchment V7H004
Catchment V7H008
Date taken: 10 July 1992; Scale : approx. 1:50000; Flight/Job no. 966; Strip no. 1; Photo no. 0427. Source: Chief Directorate of Surveys & Mapping, Private Bag, Mowbray, 8010.

Plate 22 Aerial view of the Ntabamhlope catchments in 1992.

3. METHODS

3.1 DATA COLLECTION

3.1.1 Streamflow

Weirs were built across the streams in each of the catchments to impound the water in a stilling pond so that it must pass through a sharp-crested 90° V-notch surmounted by a 1.83 m (6 ft) rectangular notch. The height of the rectangular notch varied from catchment to catchment. Plate 23 shows the construction of the Bosboukloof weir in 1937.

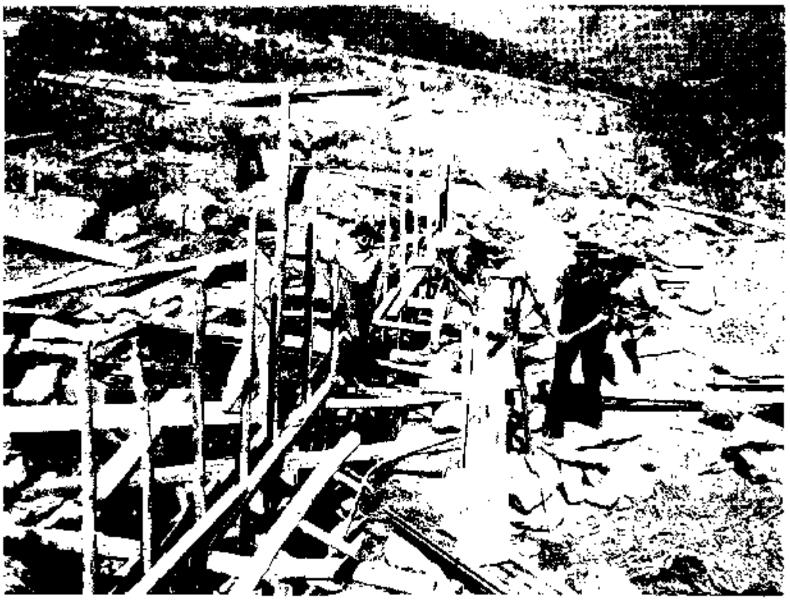


Plate 23 Construction of the Bosboukloof weir in 1937.

Langrivier had the wall raised by 2 ft and a compound notch added to the existing one in 1976 to allow for excessive floods to be measured. Plates 24 and 25 show floods in Langrivier before and after the wall was raised.

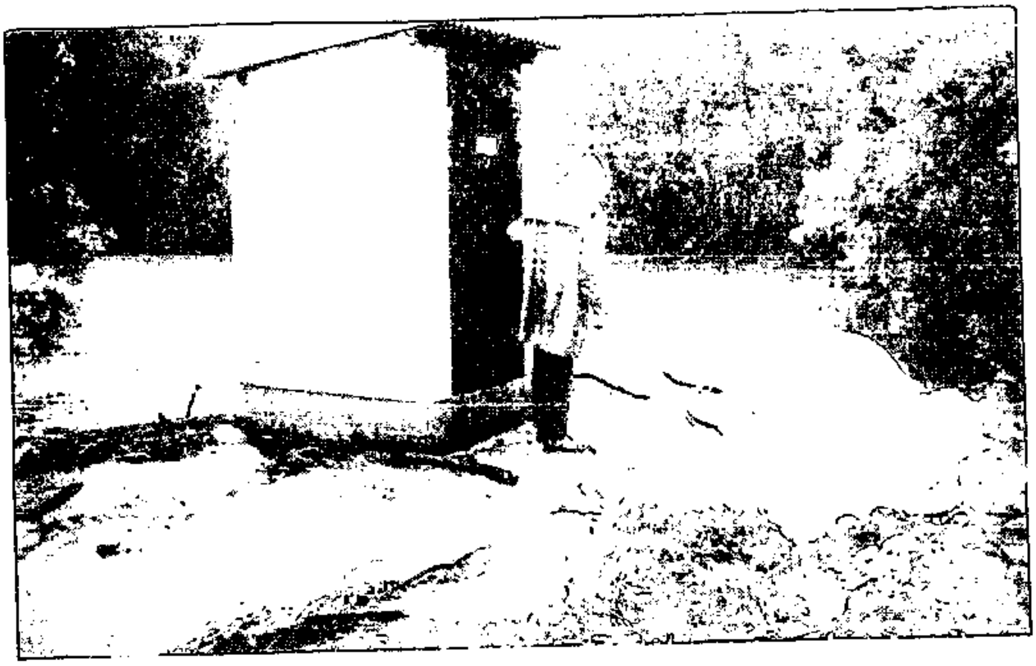


Plate 24 View of Langrivier weir overflowing during a flood on 30/04/72. Note the debris on the side, indicating that the flood had already started subsiding.

Plate 25 View of Langrivier weir during a flood on 23/11/76, two months after the wall was raised by 2 feet.

Automatic streamflow recorders were used at all the stations to record the level of the water in the stilling pools above the weirs, and the discharge computed originally by applying Barnes' empirical formula (Wicht, 1939) and, more recently, by using discharge rating tables drawn up by the Directorate of Hydrology, Department of Water Affairs and Forestry, after detailed surveys of each weir during 1984 and 1985.

Recordings in Jonkershoek started using clock-driven Kent waterlevel recorders. The recorders at Bosboukloof, Tierkloof, and Langrivier had a maximum chart range of 4 feet, while the ones at Lambrechtsbos A, Lambrechtsbos B and Biesievlei had a maximum chart range of 2.5 ft. Plate 26 shows the completed Biesievlei weir in 1938 with Kent Recorder. The height of the water through the V-notch, however was not limited. The Kent instruments were therefore replaced by Belfort FW-1 waterlevel recorders in1961, which gave a better resolution, and an unlimited chart range.

Plate 26 The completed weir of Biesievlei in 1938, with compound 90° V-notch, starting to fill up for the first time. Note the Kent recorder on the far side of the weir.

Plate 27 is a close-up photo of the Belfort recorder.

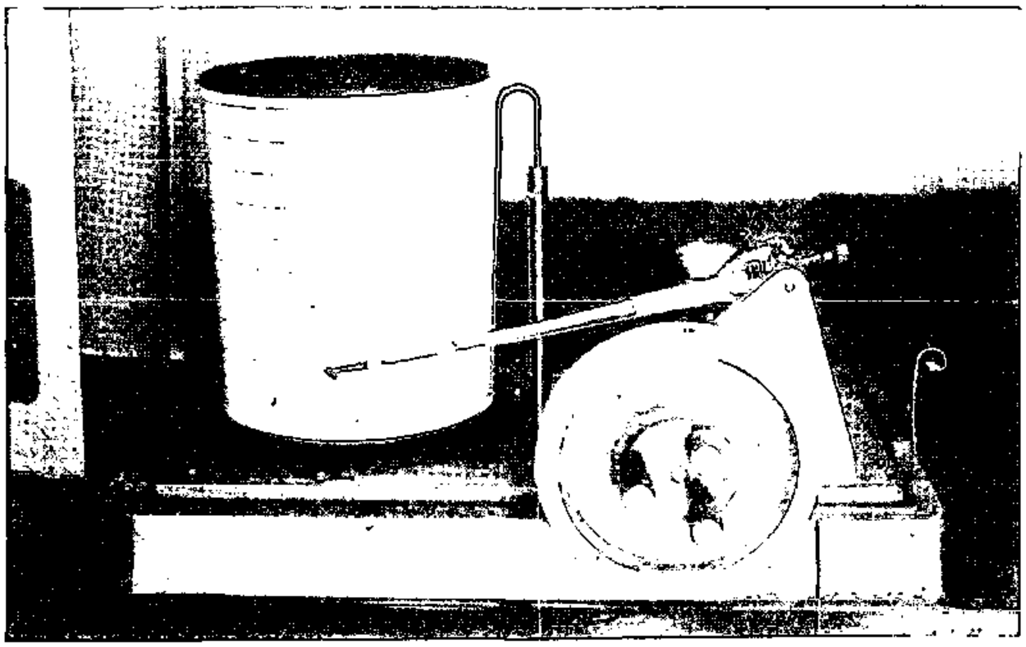


Plate 27 A close-up view of the Belfort FW1 water level recorder.

Streamflow measurements at Cathedral Peak started off in 1948 with the use of Friez Model FW-1 and Stevens Type F clock-driven chart recorders (Nänni,1956). These were replaced by Belfort recorders in 1961. During March 1989 the stations were automated and MC Systems shaft encoders with float and counterweight coupled to MC Systems data loggers were used. These were run in conjunction with the Belfort recorders for a couple of weeks before the Belforts were removed. This allowed for visits to be done on a bi-weekly basis.

The weirs at Witklip were built in 1974 and streamflow measurement commenced in January 1975, using Belfort recorders. A leak in the stilling weir of Catchment 3 was repaired in September 1976. Measurements at Catchments 5 and 6 were stopped in September 1990, whilst streamflow at Catchment 3 was automated using a MC Systems data logger and encoder. Catchment 3 was closed in March 1996.

The stilling weirs at Mokobulaan were built in 1956 and streamflow measurement commenced in November 1956 using OTT Type X water level recorders. These were replaced in September 1961 with Belfort recorders. During 1986 the stations were automated and MC System shaft encoders with float and counterweight coupled to MC Systems data loggers were installed.

The stilling weirs at Westfalia were built during 1972 and 1973 and streamflow measurement commenced as each weir was completed. Belfort recorders were installed and are still in use. Streamflow measurement in Catchment C was stopped in September 1990.

At the time of the weekly visit to the weirs to change charts, levels of water flowing through the V-notch were checked using calibrated hook gauges. In 1971 glass manometers and brass staff gauge plates placed on the outside of the walls of the Jonkershoek catchment weirs replaced the hook gauges. This was done to get a more accurate water level reading during windy days when the turbulence of the water surface was too severe to obtain accurate readings with the hook gauge.

3.1.2 Rainfall

Rainfall at most sites was collected using a Standard Meteorological Office raingauge. These are based on the "Snowdon" type raingauge, which has a 127 mm diameter funnel with a sharp, rigid rim of brass, and a copper collecting bucket. They were erected vertically irrespective of slope, with the orifice 1.2 m above ground and were referred to as the "A" gauge. However, in high wind situations, as experienced in Jonkershoek, an eddy effect causes these unshielded gauges to not record the true amount of rain that falls (Wicht,1944). In 1941 Wicht did a study at Jonkershoek on various types of shielded and unshielded raingauges and in line with other research done on this subject, concluded that shielded raingauges will give a more accurate rainfall catch than unshielded ones. The shielded gauges basically incorporated a screen similar to the one invented by Nipher in 1878 (Wicht, 1944) and should be erected perpendicular to the slope of the site. Subsequently these raingauges, commonly referred to as "B" gauges, later replaced the standard "A" type gauge at Jonkershoek. The shielded "B" gauges were also used at all the other experimental sites.

In 1937 sixteen of the "A" type raingauges were placed at relatively high, intermediate and low altitudes sites in each catchment at Jonkershoek (Wicht, 1944). In 1944, "B" raingauges were erected next to the "A" gauges. The two types of raingauges were run together until 1971 when the "A" gauges were closed down. Some additional "B" type raingauges were erected in Jonkershoek, bringing the total number of raingauge sites to 25. Some have since been closed down. Table 8 is a list of the current by maintained raingauges in Jonkershoek.

Table 8 The currently maintained rain-gauge network in the Jonkershoek research catchments.

Catchment	Number of sites	Interval visited	Gauge number*
Bosboukloof	1	Weekly	(11A & 11B)
	2	Monthly	(5B & 25B)
Lambrechtsbos B	1	Weekly	(15A & 15B)
Biesievlei	2	Weekly	(19A & 19B, 12B)
Tierkloof	2	Weekly	(9B, 13A & 13B)
Langrivier	2	Weekly	(8B, 14A & 14B)

* The A gauge represents a Casella chart recording rain-gauge, while the B gauge with the same number is a standard rain-gauge next to the Casella. It is used as a check gauge.

Meanwhile, at six selected raingauge sites in the Jonkershoek catchments, continuous rainfall measurement was done with Casella siphon rainfall recorders. Orifices of 8 inch (203 mm) were used from the start of installation (1937) until 1972, when they were replaced by 5.058 inch (129 mm) orifices. Each Casella recording raingauge was paired with an "A" gauge (later a "B" gauge) for calibration and checking purposes. All rainfall data used in this study are derived from the Casella gauges.

Cathedral Peak had 14 Casella recording raingauges, of which four were operating in the three catchments reported on. Orifices of 5.058 inch (129 mm) were used from the start of recordings. Each Casella was also paired with a standard 127 mm Snowdon "B" raingauge. Standard weekly and monthly raingauges with Nipher shields were also placed at various elevations in all the catchments, bringing the total in Cathedral Peak in 1956 to 25 (Nänni, 1956).

Continuous rainfall measurement in the three analysed catchments at Witklip was done with 5 Casella siphon rainfall recorders. These started recording in October 1974 using orifices of 5.058 inch (129 mm). These Casella raingauges were each paired with "B" gauges. Raingauges RA3 and RA6 were automated in September1989 using tipping bucket raingauges and MC Systems data loggers. Rainfall measurements at Witklip were terminated in March 1996.

Continuous rainfall recording at Mokobulaan started off in 1956 with a 5.058 inch orifice Casella recorder (R3) in Catchment B, that was situated close to the weir. "B" gauges were placed at upper and lower elevations in each of Catchments A and C, with one "B" gauge in the upper part of Catchment B (Nänni, 1971). In September 1971 another Casella recording raingauge (R4) was added to the "B" gauge in the upper part of Catchment B. In Plates 16 and 17 the location of raingauges R3 and R4 in Catchment B and raingauges 1 and 2 in Catchment A can clearly be seen as clean open circles in the plantation. In 1980 another raingauge site (R8) was installed outside the pine plantation and below the weir to replace R3, because trees were encroaching upon it. In 1986 the Casella raingauges were replaced with tipping bucket raingauges coupled to MC Systems data loggers, allowing the site to be visited on a monthly basis.

The rainfall network at Westfalia consisted of 5 Casella recording raingauges, with one in Catchment A, and two each in Catchments B and D. Each was paired with a standard "B" gauge. In 1992 the lower gauge in Catchment D was closed down and the two gauges in Catchment B were converted to standard monthly gauges.

3.2 DATA HANDLING

Charts are digitised using a chart digitizing system, which transforms analogue data on autographic recorder charts to electronic-medium data by means of a digitizer. The original detailing of this process was described by Meyburgh *et al.* (1970). Electronic data from the digital loggers are read into the system as ASCII formatted data files. The data from each chart and data logger (streamflow, rainfall, thermo-hygrograph, wind speed and wind direction) are stored as time-height values. Each parameter has its own data directory with date-named files that collectively keep all time-height values from digitized charts. For example, all streamflow data (digitized and electronic) of all streamflow stations for the year 1983 are stored in file STREAM.83.

The digitizing system also has a facility where data can be extracted. The following formats are available for rainfall and streamflow:

☐ **Rainfall**

- Breakpoint data (digitized points on charts or original data from loggers)
- rainfall totals for hourly, daily, weekly, monthly, or annually in tabular form with date, time, rainfall, time increment, rainfall intensity, and accumulated rain.

☐ **Streamflow**

- Breakpoint data (digitized points on charts)
- Stream flow volumes: summed by hour, day, week, month, year; in m^3 and streamflow depth (mm).
- Storm flow: start time, completion time, duration, initial discharge, peak discharge, total storm flow, total quickflow, time to peak (TTP), recession limb time (TR), rising limb quickflow (QTP), recession limb quickflow (QR), ratio of TR/TTP, ratio of QR/QTP.

To generate streamflow volumes, the program uses discharge rating tables unique to each streamflow station. If a station does not have its own set of rating tables, Barne's formula is used.

3.3 ANALYSIS OF DATA

The paired catchment approach was used to assess the effect of a vegetation cover treatment on streamflow (Hewlett and Pienaar, 1973). The method is based on the assumption that the relationship between the streamflow of two physiographically similar catchments will remain the same provided that the vegetation of these catchments remains the same or changes in a similar fashion. Streamflow in each of the treatment catchments was calibrated against their control catchments over a pre-treatment period when the vegetation in each was mature and did not change.

An index of catchment antecedent wetness (Dunne and Leopold, 1987) was tested as a predictor variable in the calibration models as an adjunct to the control catchment streamflow. The antecedent wetness index for any week *i* (AW_i) was calculated from weekly rainfall as follows:

$$AW_i = D\,(AW_{i-1}) + P$$

where *P* is the weekly rainfall in the treatment catchment, *D* is an arbitrarily selected decay factor (usually between 0.8 and 0.97) and AW_{i-1} is the wetness index for the previous week. A second antecedent wetness index with a much higher decay factor (0.2) was sometimes tested where the calibration model was weak.

Only where the control catchment did not provide a high level of explanation of the variation in the treatment catchment streamflow were the antecedent wetness indices necessary in the calibration equations.

Several regression models were tested to best express the relationship between flows in the treatment and control catchments during the calibration periods. Model selection was done on the basis of adjusted-R^2 (proportion of variance explained) and an inspection of residuals. Additional criteria used to select between apparently suitable models were minimising PRESS (prediction error sum of squares), minimising auto correlation in the residuals and general simplicity. A weak regression model reduces the chances of detecting a significant treatment effect, and also means that wider confidence limits will result around the predictions from the model. The selected calibration models are shown in the of tables, one for each treatment catchment, that indicate the predictor terms in the model, the values of the regression coefficients and the fit of the models (adjusted R^2) and error degrees of freedom.

The significance of any treatment effect (afforestation or clearfelling) was assessed by the dummy variable method of multiple regression analysis (Draper and Smith, 1966). The t-test for entry of a dummy variable into the regression models can be shown to be the equivalent of an F-test for the extra sum of squares due to the entry of an additional term into the model (Kleinbaum and Kupper, 1978). The application of this multiple regression technique for the analysis of paired catchment experiments is described fully in (Hewlett and Bosch, 1984) and (Scott and Van Wyk,1990).

The calibration regression models were used to predict values of each of the dependent variables (treatment catchment streamflow) for the post-treatment period. Where a significant effect was found, the difference between these predicted values and the actual measured values (i.e. the deviations from the calibration relationship) were generated to indicate the nature and extent of any response in the dependent variables to the treatment.

4. THE EFFECTS OF THE AFFORESTATION/CLEARFELLING ON STREAMFLOW

4.1 CALIBRATION MODELS

The foundation of an accurate estimate of streamflow changes following treatments is a tight calibration model. The extent to which this was achieved is shown in the tables containing the calibration models. Here the type of model and the predictor terms in the various calibration models is given. In most cases the best two calibration models are presented; frequently the best model where the dependent catchment streamflow has not been transformed, and a second where it has been log transformed. The log transformation is typically successful at removing heterogeneity of the variance in the residuals of hydrological data, and it often improves the fit of the calibration model. In the case of the afforestation experiments there was typically a long pre-treatment period, which allowed a robust calibration model to be developed. The length of the calibration period can be judged from the error degrees of freedom of the calibration models (last column in the calibration model tables), bearing in mind that the unit is weekly streamflow volume (the number of weeks of calibration less one more than the number of terms in the model equals the error degrees of freedom).

A tight regression model (one which explains most of the variability in the treatment catchment's streamflow) is desirable as it narrows the confidence limits around the predictions of the dependent variable. This makes it possible to detect small changes as a result of treatment and to predict future expected flows with greater confidence. The weaker the regression model, the more difficult it is to detect a treatment induced change, and the broader the confidence bands will be around the flows predicted by the calibration model.

The residuals (deviations about regression) of hydrological data typically have a sequential pattern, causing a positive auto-correlation. This was found, usually, to be higher in the log transformed models. Auto-correlation means that the deviations of adjacent observations are likely to not be independent of each other. This phenomenon is more prevalent when working with sums taken over short intervals (days or weeks) and is less likely when working with monthly totals. Statistical advice was that the auto-correlation would lead to weaker models (less of the variance explained and broader confidence limits) but that it was not expected to influence the results. The main exception to the long pre-afforestation calibration periods is the Bosboukloof catchment (Jonkershoek) which was the first catchment to be gauged and the first catchment afforested. By the time the gauging of the primary control catchment in Jonkershoek (Langrivier) had commenced the afforestation of Bosboukloof was complete. In this case we tried to develop a calibration model using the weekly rainfall and two antecedent wetness indices. This was not entirely successful as there was large variability about the calibration model and as wetness index may not be a particularly suitable main predictor term as it is a somewhat arbitrary variable. Eventually, the early part of the rotation in Bosboukloof was used as the calibration period on the assumption that flow would have been little effected during the early part of the rotation. The other exception to the adequate calibrations is the eucalypt-afforested catchments at Ntabamhlope, V7H004 & V7H008. These were not planned experiments, but were rather a case of opportunism. These catchments were two of many catchments established at the Ntabamhlope Agricultural Research Station during the 1960's and had been gauged for a period soon after establishment before being closed. In 1990 these catchments were part of the land being afforested by Masonite Ltd, and so the opportunity was presented to re-start the gauging and to measure the effects of these plantings. The calibration periods had to be patched together from overlapping records in the early 1970's, and the data are somewhat scanty because of the logistical difficulties in keeping these stations running in recent years.

In the case of the clearfelling experiments the requirements for a control catchment are less stringent as the post-treatment period need not be as long. The treatment effects are likely to be of fairly short duration as most catchments would be returned to commercial timber crops after felling. Therefore the control catchment need only have been under stable vegetation cover for a reasonable calibration period and the expected treatment period. The calibration period is simply one during which the vegetation in both catchments was relatively stable. For these comparisons the control catchment need not be unplanted: provided it remains under a stable vegetation cover it can provide a baseline against which treatment effects can be measured. Thus, for clearfelling experiments, companion afforested catchments could be used as control catchments. In many cases this allowed for the selection of better control catchments in that tighter calibration regressions could be developed.

The long-term control catchment for the set of Jonkershoek catchments is Langrivier. As can be seen from the characteristics of this catchment and its neighbours in the listing in Table 3, Langrivier is atypical of the Jonkershoek catchments. It is larger, wetter and, more pertinently, it has a different response characteristic to rainstorms, with the result that there is a strong seasonal variation between the flows in Langrivier and the treated catchments. As a result, calibrations developed with Langrivier as the control are not particularly tight (adjusted R^2 values are low, ranging from 0.86 to 0.94 for total flows, and from 0.41 to 0.74 for low flows). By contrast, where Lambrechtsbos-B was used as the control for tests of the clearfelling of Bosboukloof and Biesievlei much tighter regression models were established (adjusted R^2 values 0.93 to 0.98; Tables 9, 10).

The low flow periods generally correlate less well between catchments as the Langrivier recessions are a different shape from the other catchments lower down in the valley. For this reason and because of the smaller data sets, the calibration models for low flow effects are weaker than the equivalent models for total flow. In extreme cases no calibration model could be established on low flows because it simply was not possible to predict them with any confidence (Bosboukloof initial planting, Biesievlei low flows generally).

4.2 PRESENTATION OF RESULTS: FLOW REDUCTIONS AND INCREASES

The **total flow** and **low flow** reductions or increases over time following treatment are illustrated in a series of figures. These figures are standardised in the following way:

1. All results are scaled to the level of a 10% planting / or the effect per 10% of the catchment treated assuming a linear relationship with area (i.e. the effects were divided through by the percentage afforestation in the catchment and multiplied by 10).
2. The solid symbols (squares and triangles) illustrate the relative change (left-hand axis) as estimated from the two best calibration models (where available).
3. The absolute changes in flow are plotted as open symbols against the right-hand axis.
4. Superimposed on the plots of flow reductions following afforestation are the predicted flow reductions (solid line) from the general empirical models of Scott and Smith (1997) as an illustration of the performance of these models.

The same results, but not standardised, are tabulated in total and low flow tables, where the significance of effects in specific years is also indicated. In these tables the mean effect over several years (usually five) is also shown. These results show the large variability in the estimated absolute and relative changes in flow as a result of the treatments. In most experiments the treatment effects are marked and obvious, making statistical tests of significance largely academic. The statistical tests simply confirm what is apparent: namely the change in streamflow following treatment is highly significant in virtually all cases.

However, what is also clear from the plots of effects over time is that the general empirical models provide only an average and long-term estimate of the reductions caused by afforestation. There is a substantial variation in the key components: time to initiation of flow reductions after planting, size of reductions in individual years, and size of effects in the later years of long rotations.

4.3 SEASONAL EFFECTS

A series of bar graph figures illustrate the seasonal pattern of flow changes as measured in the various experiments. The results that are plotted are monthly means of the results over several years during the mature stage of the plantation's life, typically when the plantation was causing the largest reductions in streamflow. These monthly means illustrate a similar point to that shown by the separate total flow and low flow figures in the tables of results: the relative effect of trees on low flows (or dry season flows) is generally greater than the effect during the wet season. This additional impact on low flows varies fairly widely, but is seldom greater than 20% more than the impact on total flows. There are a few anomalous results in this series of plots, such as a zero impact on flows on a single month (Figure 30) but this result is thought to be simply coincidental. There is normally a moderate degree of auto-correlation in the residuals of the calibration models. It is therefore not unusual that the deviations in flow for a single short interval are all high or low. It is possible that a sequence of such events could occur on a specific month over several years, and this is thought to have happened in the case in Figure 30 where there are few post-treatment years.

4.4 BOSBOUKLOOF: INITIAL AFFORESTATION (57% *PINUS RADIATA*, 1940)

As mentioned earlier, Bosboukloof was first gauged catchment in Jonkershoek, and the first to be planted (1940). As a result there is no pre-planting calibration period with the Langrivier control catchment which was only gauged from 1942 onwards. The effects of the initial planting of Bosboukloof were therefore estimated by using Langrivier flow as the control and the first four years of paired streamflows as the calibration period. The absence of a pre-treatment control is expected to cause some level of underestimate of the afforestation effects. However, a sound and simple calibration was established for total flows using monthly streamflow volumes (Table 9) though no low flow model could be developed. The estimated flow reductions from planting until clearfelling commenced in 1979 are plotted in Figures 1 and 2 and tabulated in Table 10.

Table 9 Details of the **calibration models** used in the analysis of streamflow in **Bosboukloof** for initial planting and clearfelling. No low flow model was possible for the original planting experiment.

Dependent Variable	Model	Intercept (β_0)	Regression coefficients (β_1, β_2)	Adjusted R^2	Error d.f*
Bosboukloof: Plant Total flow †	$T = \beta_0 + \beta_1 \ln Lr$	1.0264	0.5831	0.8	51
Bosboukloof Clearfell: Total flow 1	$T = \beta_0 + \beta_1 Lb + \beta_2 AW + \beta_3 AW2$	-0.9069	1.0814 0.0167 -0.0235	0.96	205
Bosboukloof Clearfell: Total flow 2	$\ln T = \beta_0 + \beta_1 \ln Lb + \beta_2 . \log AW$	-1.7356	0.6648 1.0953	0.98	206
Bosboukloof Clearfell: Low flow 1	$T = \beta_0 + \beta_1 . \ln Lb + \beta_2 (Lb)^{1/2} + \beta_3 . AW$	1.8277	1.9657 -3.4894 0.0101	0.98	53
Bosboukloof Clearfell : Low flow 2	$\ln T = \beta_0 + \beta_1 . Lb + \beta_2 (Lb^{1/2} . AW) + \beta_3 \log AW$	-3.0316	0.2755 -0.0004 1.7289	0.97	53

T = streamflow (mm) from treated catchment, Bosboukloof
Lr, Lb = streamflow (mm) from control catchments, Langrivier and Lambrechtsbos - B, respectively
Ln = indicates natural logarithm
AW, AW2 = antecedent wetness by two decay factors, 0.91 and 0.2 respectively
* d.f. = degrees of freedom
† = monthly volumes over the early part of the rotation (1942-1945) were used as the control period.

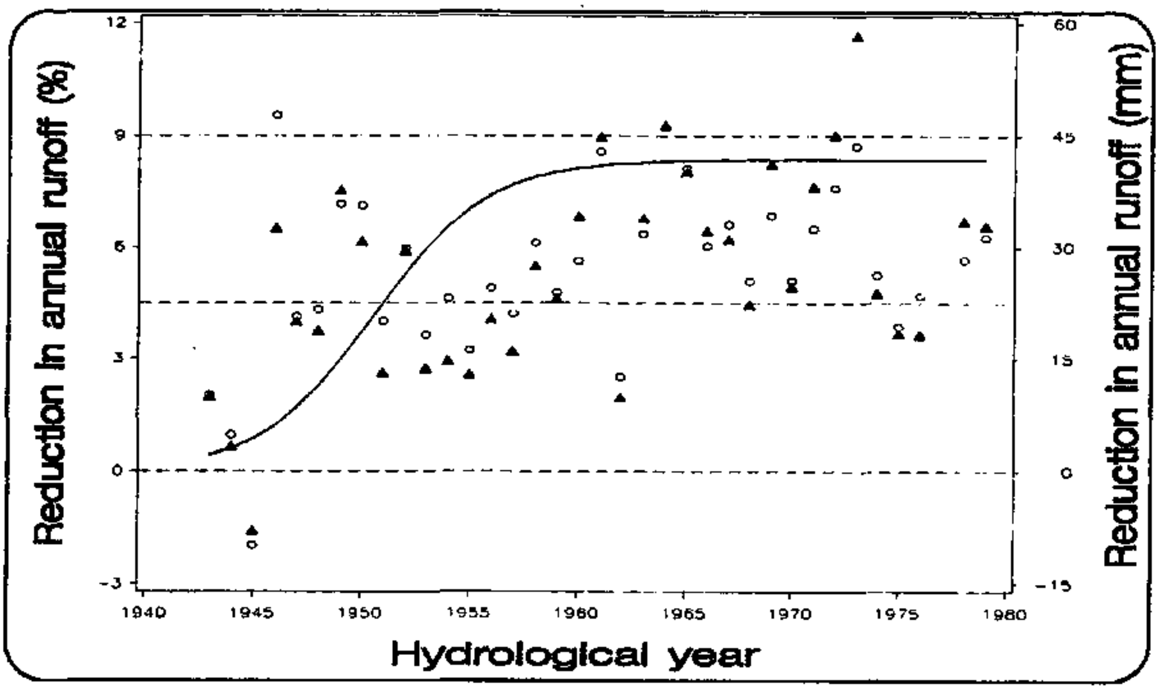


Figure 1 The estimated relative **reductions (▲)** and absolute reductions (open circles) per year in **total flow** in **Bosboukloof** following 57% planting to pines in 1940. The vertical axes are scaled to a 10% level of planting. The solid curve represents the reductions predicted by the empirical model of Scott and Smith (1997).

Statistically significant reductions in streamflow were observed in the first post-calibration year (1946) just six years after planting and in all years thereafter. Flow reductions are high from an early age, vary widely and do not show a clear incremental pattern over time. Peak reductions occur at around 22 years of age at around 44 mm/10% planted (9%/10% planted) and are maintained for roughly ten years. Thereafter there appears to be a decline in the impacts of forestry, though the pattern is not particularly distinct. The 1977 hydrological year was exceptionally wet, and the calibration model seems to have broken down under these conditions, appearing to dramatically under-predict flows during this year (Table 10).

Table 10 Reductions in **total flow** in **Bosboukloof** catchment, Jonkershoek, 57% afforested with *Pinus radiata* in 1938-1940. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)
0	1941	1632	-		-
1	1942	1318	-		-
2	1943	1036	-		-
3	1944	1360	-		-
4	1945	1427	-		-
5	1946	1060	273.4	37.9	37.0
			45.6		**6.2**
6	1947	1010	118.4	36.4	22.9
7	1948	1148	123.8	36.4	21.4
8	1949	895	204.8	36.7	42.9
9	1950	1236	203.6	36.4	35.1
10	1951	1217	115.0	38.5	14.9
			153.1		**26.2**
11	1952	1096	170.9	36.5	33.6
12	1953	1330	104.2	37.0	15.6
13	1954	1273	132.8	39.0	16.7
14	1955	1005	92.7	36.6	14.8
15	1956	1016	140.6	36.5	23.3
			128.2		**20.0**
16	1957	844	120.9	36.9	18.3
17	1958	1102	175.2	36.4	31.4
18	1959	1180	137.2	36.4	26.4
19	1960	902	161.4	37.3	38.9
20	1961	999	245.6	36.6	51.1
			168.0		**31.9**
21	1962	1352	72.2	36.7	11.3
22	1963	888	182.0	36.7	38.6
23	1964	1048	264.2	36.5	52.9
24	1965	989	232.3	36.5	45.7
25	1966	914	172.7	36.7	36.7
			184.7		**35.6**
26	1967	1158	189.3	36.4	35.4
27	1968	1086	145.8	36.4	25.4
28	1969	858	196.2	37.2	46.9
29	1970	1197	146.1	36.4	28.1
30	1971	865	186.1	37.1	43.4
			172.7		**34.9**
31	1972	949	217.4	37.2	51.4
32	1973	792	249.8	37.9	66.5
33	1974	1413	150.6	36.4	27.2
34	1975	1149	111.0	36.4	21.0
35	1976	1544	134.6	36.8	20.8
			172.7		**34.1**
36	1977	1564	-172.2	38.3	-22.7
37	1978	935	162.4	37.2	38.2
38	1979	958	179.4	36.6	37.4
			56.5		**10.2**

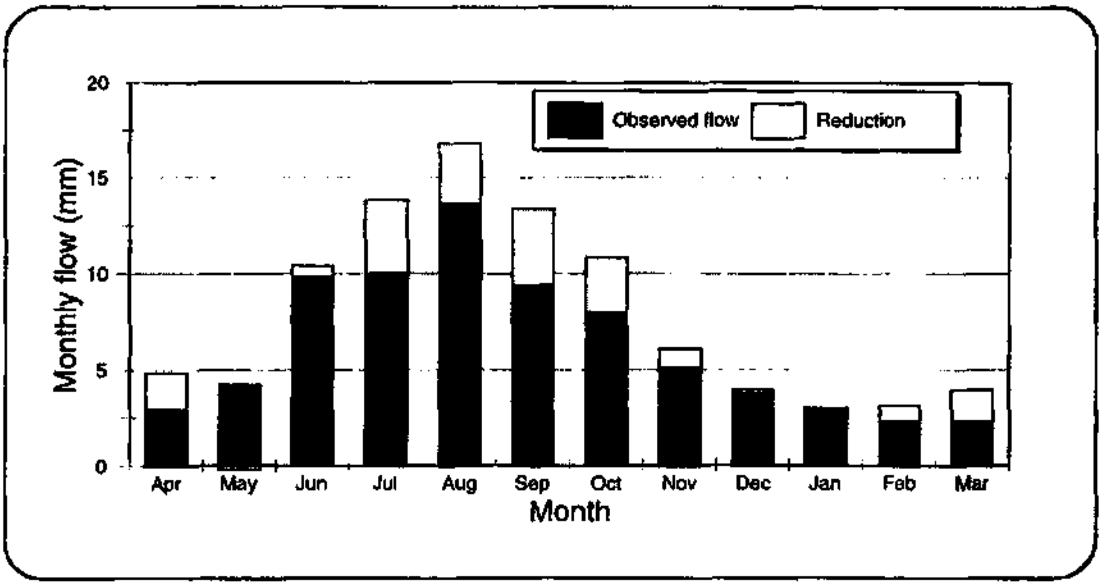


Figure 2 The mean monthly observed flows and estimated reductions as a result of afforestation in **Bosboukloof** over the period 1952 to 1961 once the trees were mature.

4.5 BOSBOUKLOOF: CLEARFELLING 39 YEAR OLD PINES (1979-1982)

A good calibration equation was established for the clearfelling of Bosboukloof using the neighbouring Lambrechtsbos-B as the control catchment ($R^2 > 0.96$; Table 9). During the treatment period the trees in Lambrechtsbos-B were approaching maturity. Relative to the treated catchment the control was stable, though it is likely that flows were still being progressively reduced in Lambrechtsbos-B during this period of comparison.

Clearfelling took place progressively over four years as this catchment contains a large area of plantation. As a result of the phased felling there is a gradual response in streamflow. Increases in flow were recorded in the first year of clearfelling (1979), increasing rapidly to peak in the third, fourth and fifth years after the start of felling (Figure 3, Table 11) at levels between 12 and 16% per 10% of catchment cleared, or 38 to 53 mm/10% of catchment area clearfelled. Streamflow dropped rapidly as the newly planted trees closed canopy (1984, 1985, Figure 3) but in February 1986 most of the young plantation in Bosboukloof was burned in a wildfire. In the first two years after the wildfire streamflow increased again by around 8% per 10% of catchment planted (or 35 to 38 mm per 10%, Table 11). Relative increases in low flows followed a similar pattern, but were smaller than total flow increases and somewhat lagged; low flow increases peaked in the fifth and sixth years (1983, 1984) after clearfelling started.

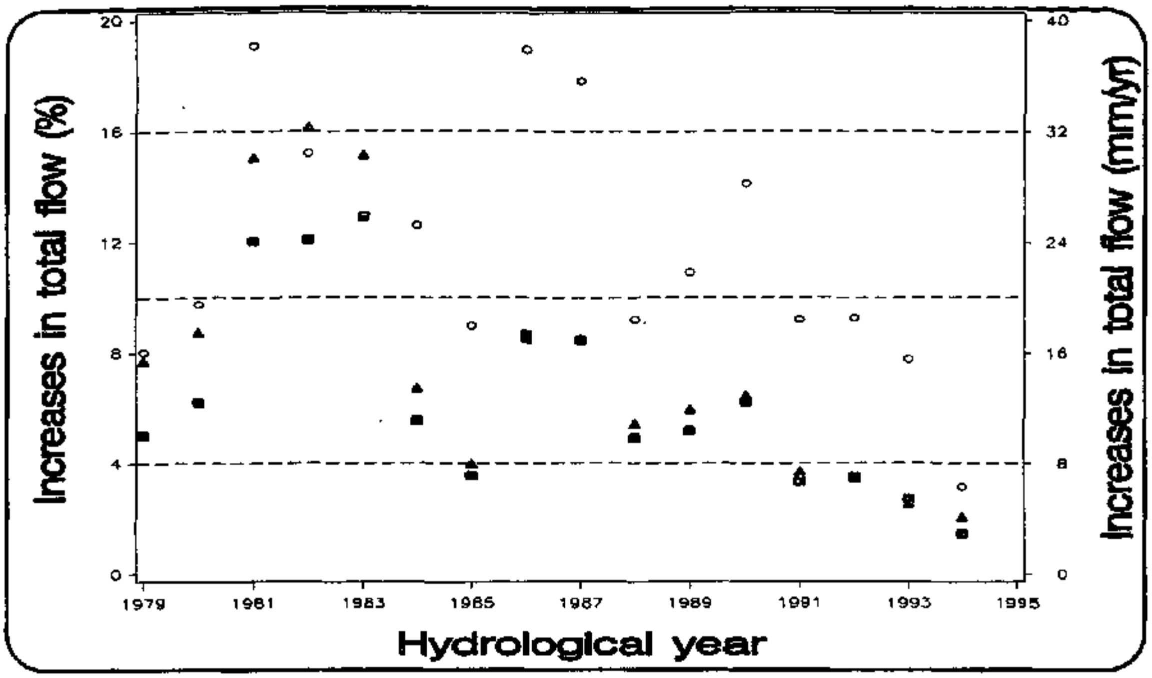


Figure 3 The relative increases in **total flow** estimated by two different calibration models (▲, ■) and absolute increases (open circles) in **Bosboukloof** following clearfelling in 1979 to1982, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

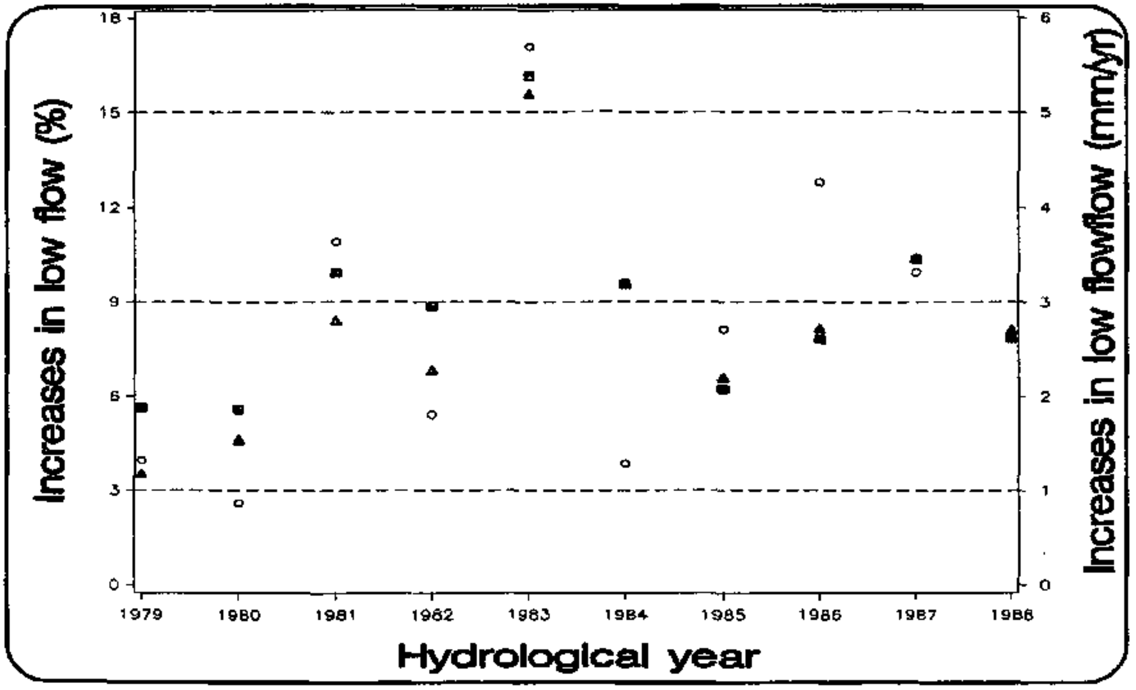


Figure 4 The relative increases in **low flow** estimated by two different calibration models (▲ ■) and absolute increases (open circles) in **Bosboukloof** following clearfelling from 1979 to 1982, plotted against the hydrological year. Responses are scaled to a 10 % level of clearing.

Table 11 Estimated increases in flows in **Bosboukloof** catchment, Jonkershoek, following the clearfelling of forty year old *Pinus radiata* between 1979 and 1982. The increase is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological year	Annual rainfall (mm)	Total flow increase (mm)	95% CI (mm)	Total flow Increase (%)	Low flow increase (mm)	95% CI (mm)	Low flow increase (%)
0	1976	1544	-22.0	14.7	-4.1	-0.4	4.8	-1.8
1	1977	1564	6.1	18.2	0.7	0.7	2.2	1.2
2	1978	935	23.3	13.6	9.7	0.8	3.0	1.1
3	1979	958	91.9	13.6	44.2	7.5	2.4	20.2
4	1980	1216	111.7	13.6	50.1	4.9	5.3	26.4
5	1981	1092	218.4	13.7	86.3	20.7	2.0	47.9
			71.6		**7.8**	**5.7**		**13.9**
6	1982	1097	174.3	13.6	92.5	10.3	3.8	38.9
7	1983	1191	305.1	13.9	86.8	32.4	2.5	88.7
8	1984	1329	144.4	13.9	38.7	7.3	6.6	54.5
9	1985	1166	102.8	14.2	22.9	15.4	2.1	37.6
10	1986	1068	217.0	14.2	48.9	24.3	1.9	46.5
			188.7		**16.1**	**17.9**		**52.9**
11	1987	1077	204.0	14.1	48.8	18.9	3.0	59.2
12	1988	1086	105.4	13.8	31.3	15.3	2.9	46.4
13	1989	1046	125.1	13.9	34.2	**17.1**		**52.7**
14	1990	1091	161.5	14.2	37.1			
15	1991	1330	105.3	14.5	21.2			
			140.3		**8.4**			
16	1992	1290	106.1	14.7	19.9			
17	1993	1273	89.1	15.1	14.7			
18	1994	929	36.2	13.7	11.9			
			77.1		**3.2**			

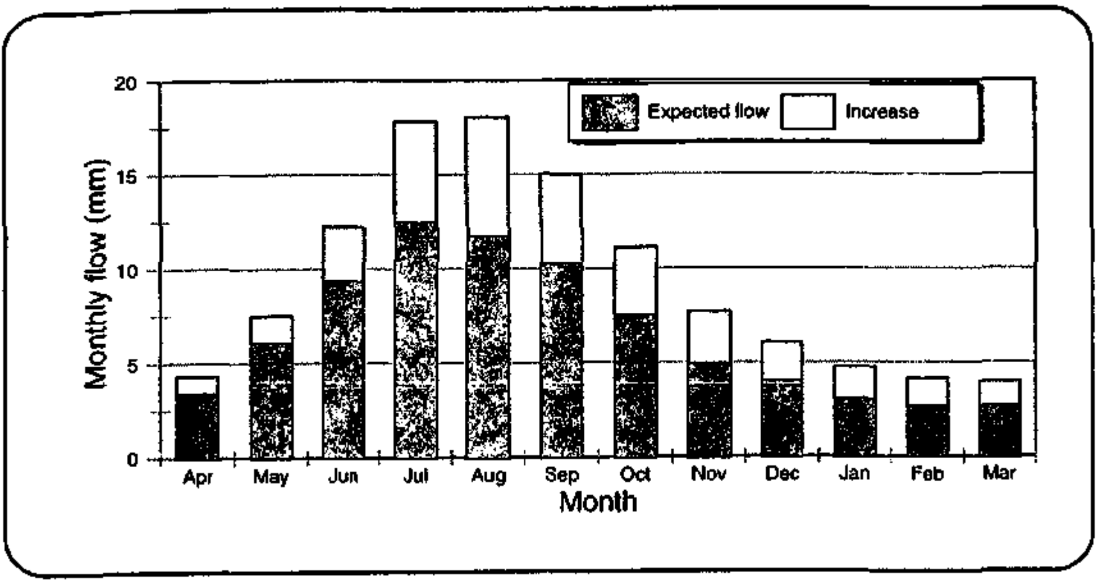


Figure 5 The mean monthly expected flow and estimated increase as a result of **clearfelling** in **Bosboukloof** over the 10 years from the start of clearing (1979 - 1988).

4.6 BIESIEVLEI: INITIAL AFFORESTATION (98% *PINUS RADIATA, 1948)*

The calibration for total flow is based on Langrivier and is sound, but the low flows taken separately are difficult to model (Table 12). The suspicion is that Biesievlei, being a small, low elevation catchment, has summer low flow augmented by subsurface leakage into the catchment: low flows are remarkably sustained while low flows in Langrivier recede quite strongly through the season. Quantitatively such gains may not be important, but the pattern of low flow recession is definitely different.

Table 12 Details of the **calibration models** used in the analysis of weekly streamflow changes in **Biesievlei** after planting in 1948 and clearfelling (cf) in 1984 and 1985.

Dependent Variable	Model	Intercept (β_0)	Regression coefficients (β_1, β_2)	Adjusted R^2	Error d.f*
Biesievlei : Plant Total flow 1	$\ln T = \beta_0 + \beta_1 AW +$ $\beta_2 . \ln Lr$	0.08647	0.003506 0.184044	0.94	310
Biesievlei : Plant Total flow 2	$T = \beta_0 + \beta_1 Lr +$ $\beta_2 (Lr^{\frac{1}{2}} . AW/100)$	2.279935	0.736502 0.736502	0.88	310
Biesievlei: Plant Low flow 1	$\ln T = \beta_0 + \beta_1 . \ln Lr +$ $\beta_2 . (Lr.AW)$	0.8515	0.3534 0.0006	0.44	126
Biesievlei : Cf Total flow 1	$T = \beta_0 + \beta_1 AW2 +$ $\beta_2 (Tk^{\frac{1}{2}} . AW/10000)$	-1.0123	-0.0077 64.2171	0.86	467
Biesievlei : Cf Total flow 2	$T = C_0 + \beta_1 Lb +$ $\beta_2 . AW2$	-0.7032	1.1858 0.0075	0.93	467
Biesievlei : Cf Total flow 3	$T = \beta_0 + \beta_1 Lr^{\frac{1}{2}} +$ $\beta_2 . AW2 + \beta (lrAW)$	2.1901	-1.5358 0.0197 61.0325	0.86	466
Biesievlei : Cf Total flow 4	$T = \beta_0 + \beta_1 . AW$ $B_2 . AW2 + B_3 . \ln AW2$	16.5615	0.0377 0.1087 -7.0632	0.83	466
Biesievlei: Cf Low flow 1	$T = \beta_0 + \beta_1 (Lr)^{\frac{1}{2}} +$ $\beta_2 \ln . Lr + \beta_3 . Lb$	34.1879	-108.0914 99.7245 5.4441	0.41	115
Biesievlei: Cf Low flow 2	$\ln T = \beta_0 + \beta_1 AW2 +$ $\beta_2 . Tk + \beta_3 . \ln AW$	1.7476	0.009485 0.2635 -0.4803	0.2	115

T = streamflow (mm) from treated catchment, Biesievlei
Lb, Lr, TkC = corresponding streamflow in Lambrechtsbos-B, Langrivier and Tierkloof, respectively
AW, AW2 = antecedent wetness by two decay factors
* d.f. = degrees of freedom

The two total flow models predict virtually the same post-treatment flows for Biesievlei (Figure 6). The flow reductions begin very early in the rotation and climb steeply to an asymptote of around 6%/10% planted and above 30 mm/10% planted after 12 years (Figure 6). These flow reductions are maintained for the remainder of the 35 year rotation (Table 13). Compared to the general flow reduction model the pattern of flow reductions is very similar, but the observed reductions are apparent much earlier in the rotation (approximately two years earlier than predicted) and the asymptote is lower than predicted (around 6% as opposed to a predicted 8.5%; Figure 6). Low flows are affected in much the same way as total flows (Figure 6; Table 13) but are clearly reduced to a much greater degree (7%/10% as opposed to 6%/10%; Figure 8), though again less than the 8.5% predicted by the general flow reduction model.

Table 13 Reductions in flows at **Bieslevlei** catchment, Jonkershoek, 98% afforested with *Pinus radiata* in 1948. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean. Five year mean effects are shown in bold.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)	Low flow reduction (mm)	95% CI (mm)	Low flow reduction (%)
0	1948	1198	-39.3	29.4	-7.1	0.7	1.4	1.3
1	1949	1003	9.1	28.1	2.2	11.5	3.0	15.9
2	1950	1367	15.7	29.4	2.9	9.8	1.5	19.0
3	1951	1671	-74.9	31.7	-10.3	2.9	5.0	9.8
4	1952	1180	40.6	29.1	7.9	12.7	1.5	24.5
5	1953	1471	71.1	31.5	9.9	10.5	1.6	21.4
			3.7		**0.6**	**8.0**		**15.5**
6	1954	1782	182.8	35.3	19.3	17.0	1.6	35.0
7	1955	1471	65.2	31.9	8.7	6.3	1.6	12.8
8	1956	1332	105.1	30.1	17.4	18.4	1.6	37.3
9	1957	1702	239.5	33.4	28.4	13.5	5.8	49.6
10	1958	1179	228.0	29.8	39.4	39.8	2.4	57.6
			164.1		**22.1**	**19.0**		**39.1**
11	1959	1365	302.3	30.6	46.8	30.9	2.2	71.2
12	1960	1048	215.0	28.3	49.2	63.2	10.0	66.8
13	1961	1137	247.6	28.5	55.1	46.0	2.2	68.3
14	1962	1576	356.6	32.3	46.2	39.4	1.7	62.5
15	1963	1235	285.4	29.3	53.1	41.8	2.1	62.8
			281.4		**49.5**	**44.3**		**66.1**
16	1964	1337	305.3	29.0	60.6	26.4	2.9	67.6
17	1965	1088	287.3	28.7	60.7	32.4	2.1	73.7
18	1966	993	291.7	28.9	58.0	43.3	1.5	71.4
19	1967	1314	315.8	30.0	53.0	22.1	3.5	61.2
20	1968	1388	344.3	30.8	52.1	18.1	5.2	61.5
			308.9		**56.4**	**28.5**		**68.0**
21	1969	889	209.3	27.9	54.8	48.0	3.0	66.4
22	1970	1307	319.6	30.3	51.2	33.5	1.4	61.3
23	1971	922	202.9	28.1	49.8	47.3	4.5	60.0
24	1972	1069	204.1	28.5	44.7	37.8	1.9	58.1
25	1973	869	185.0	27.6	54.8	60.4	10.6	62.9
			224.2		**50.8**	**45.4**		**61.9**
26	1974	1506	341.9	31.1	49.6	30.1	1.6	60.4
27	1975	1260	244.4	29.7	42.6	33.9	1.8	53.3
28	1976	1742	343.9	32.9	42.3	9.8	7.0	41.3
29	1977	1734	380.1	35.9	38.8	33.4	1.6	67.2
30	1978	1064	284.8	27.9	74.6	78.1	7.1	89.5
			319.0		**46.4**	**37.1**		**67.6**
31	1979	1019	312.3	28.3	72.1	64.7	1.9	99.6
32	1980	1340	324.8	28.5	71.8	15.6	10.1	98.2
33	1981	1189	295.1	29.1	57.0	52.9	2.0	80.6
34	1982	1146	256.5	28.3	59.2	35.2	1.8	75.1
35	1983	1229	329.3		49.2	**42.1**		**87.1**
			303.6		**61.9**			

4.7 BIESIEVLEI: CLEARFELLING OF 35 YEAR OLD PINES, 1984 & 1985

The calibration models were less satisfactory than for the initial planting (Table 13), and as a trial four different predictor terms were used; Langrivier and two planted catchments, Tierkloof (24 years and onwards) and Lambrechtsbos-B (15 years onwards), as well as a model based solely on wetness indices. The results from the better models are plotted in Figure 9. The low flow was again particularly difficult to model, and only minor parts of the variation in low flows could be predicted (Table 13). Flow increases are apparent in the first year of clearfelling (1984) when in fact just the riparian areas were cleared. As in Bosboukloof, flow increases (Table 14) peaked three to five years after clearfelling commenced. These peak increases are between 10 and 15%/10% cleared but it must be borne in mind that this percentage is calculated off a low base. Absolute increases peaked at 20 to 30 mm/10% cleared. Flow increases declined as a result of the replanting of the catchment, and had returned to pre-clearing levels within 12 years (1996; Figure 9). In other words, the pattern of flow reductions of the first rotation was being repeated.

Table 14 Flow increases following the clearfelling of the 98% afforested **Biesievlei** catchment during 1984 and 1985.

Tree age (yrs)	Hydrological year	Annual Rainfall (mm)	Total flow increase (mm)	95% CI (mm)	Total flow increase (%)
0	1984	1520	88.3	10.7	30.7
1	1985	1174	195.9	10.7	69.8
2	1986	945	343.3	10.7	114.6
3	1987	1218	264.0	10.7	94.6
4	1988	1349	280.6	10.7	121.3
			234.4		**85.0**
5	1989	1145	257.0	10.7	91.2
6	1990	1103	155.1	10.8	46.9
7	1991	1039	98.8	10.8	26.8
8	1992	1405	72.2	10.9	18.2
9	1993	1330	146.2	10.8	39.7
			145.8		**41.8**
10	1994	952	84.5	10.7	43.2
11	1995	971	54.9	10.7	21.5
12	1996	1275	-22.2	10.9	-5.6
13	1997	1142	-11.9	10.7	-4.7
			26.3		**9.6**

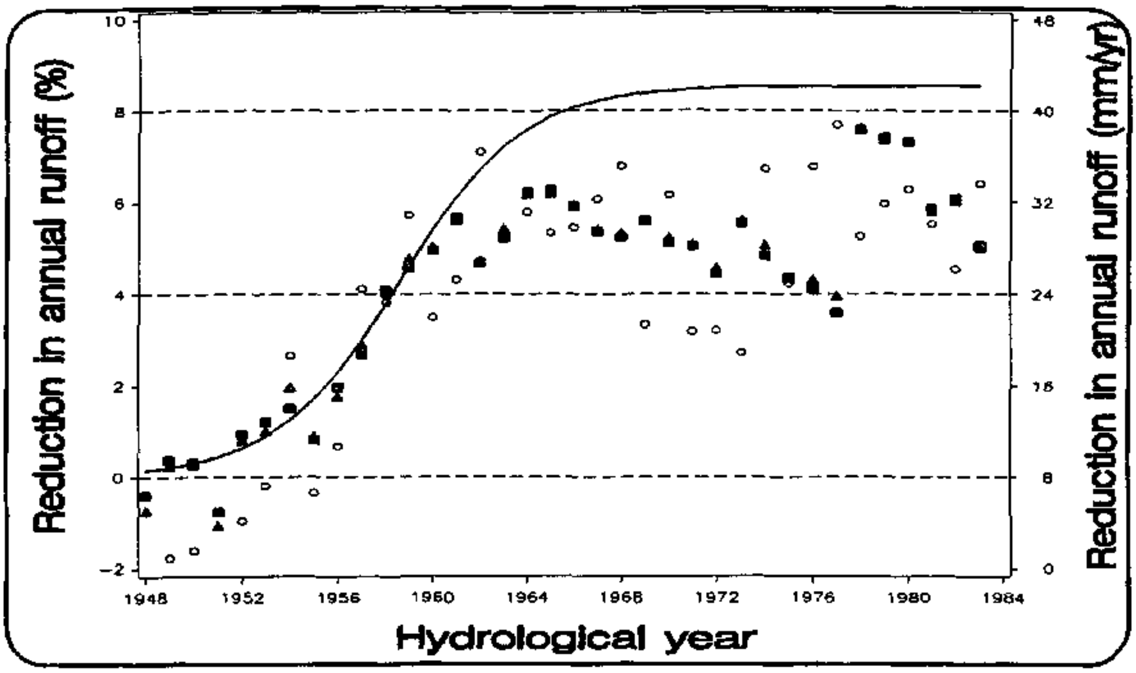


Figure 6 The relative reductions in **total flow** estimated by two calibration models (▲ ■) and absolute reductions (open circles) in **Biesievlei** following 98% planting to pines in 1948. The vertical axes are scaled to a 10% level of planting. The solid line represents the reductions predicted by the empirical model of Scott and Smith (1997).

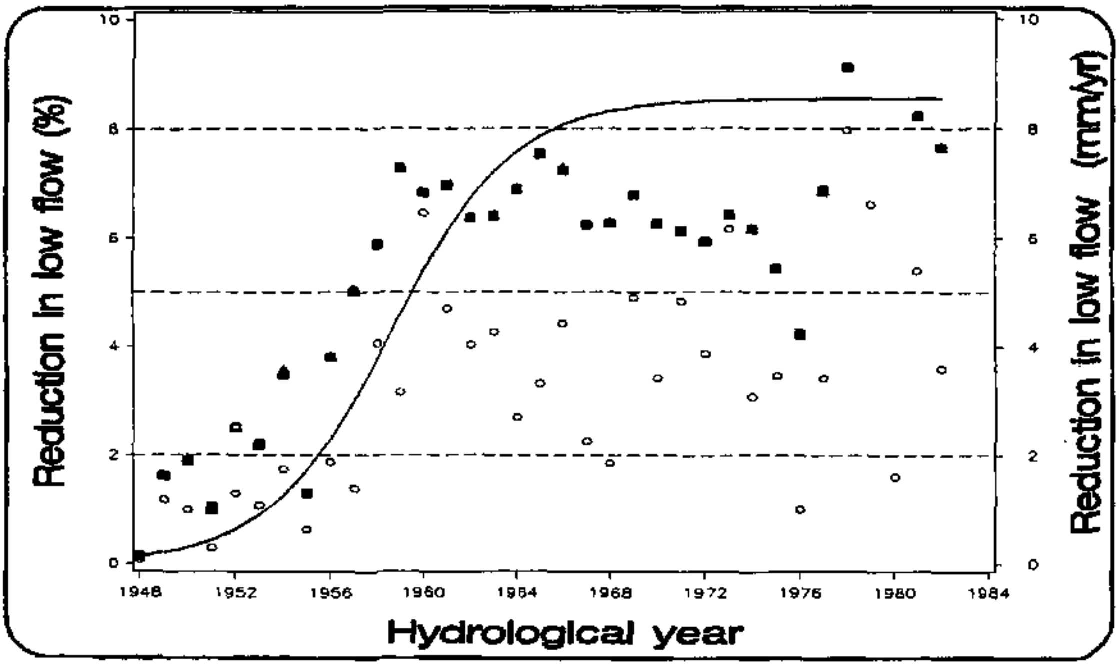


Figure 7 The relative reductions in **low flow** estimates by two different calibration models (▲ ■) and absolute reductions (open circles) in **Biesievlei** following 98% planting to pines in 1948, plotted against hydrological year.

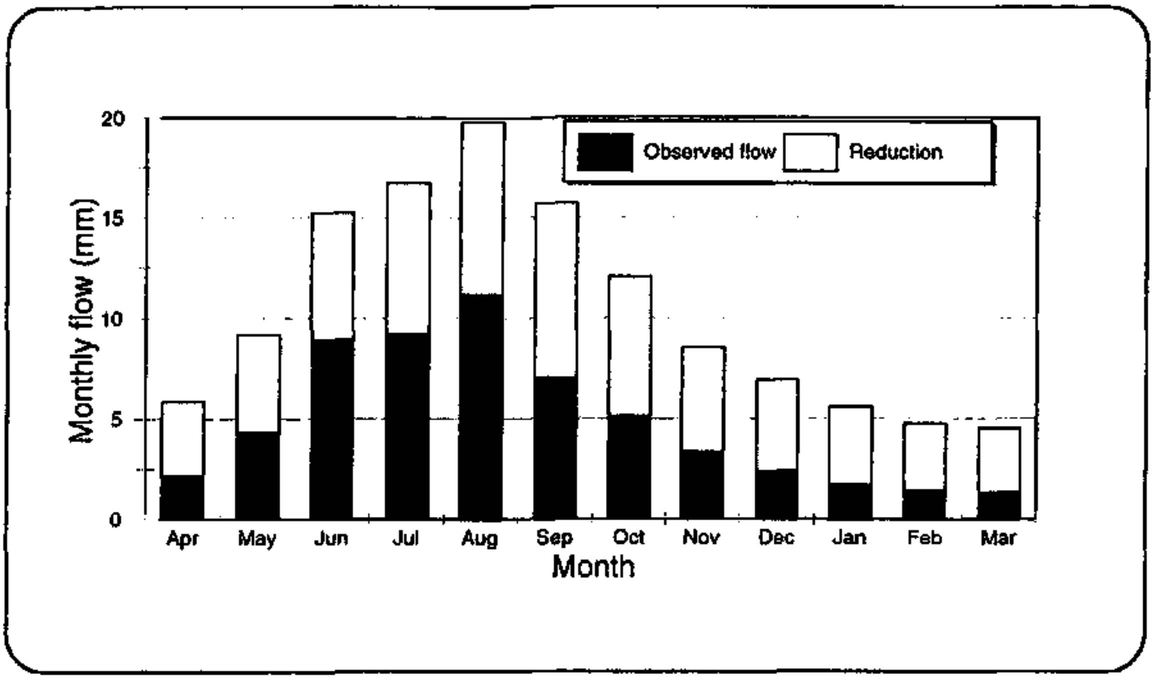


Figure 8 The mean monthly observed flows and estimated reductions as a result of afforestation in **Biesievlei** over the period 1960 to 1980 once the trees were mature.

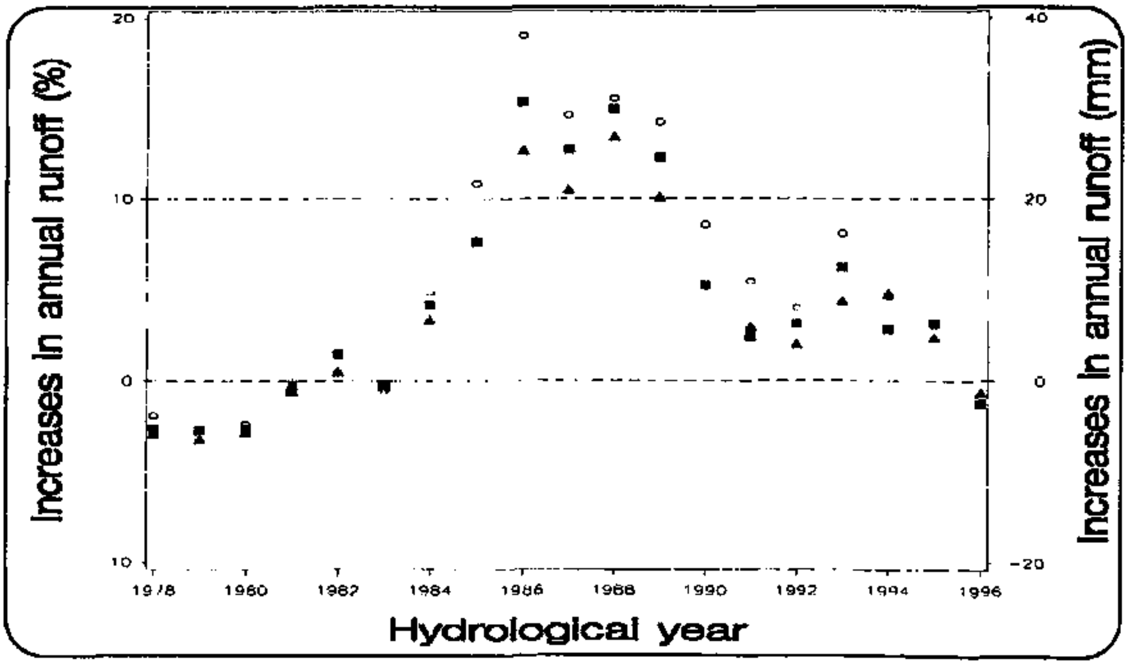


Figure 9 The relative increases in **total flow** estimated by two different calibration models (▲ ■) and absolute increases (open circles) in **Biesievlei** following clearfelling in 1984 & 1985, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

4.8 TIERKLOOF: INITIAL AFFORESTATION (36% *PINUS RADIATA*, 1956)

This is a large catchment dominated by the up-slope area comprised of cliffs and very steeply sloping talus slopes. The lower part of the catchment that was afforested has gentler slopes where soils are formed of deeply decomposed granites and a granite and sandstone colluvium mixture. This catchment is closest in locality and character to Langrivier (Table 3). As a consequence, Langrivier provides a good control for total flows (adjusted R^2 >0.93) and even the low flow calibration model is reasonable for Jonkershoek (Table 15). This is the catchment experiment in which the trees have been allowed to age longest: at 42 years the rotation is however not uncommon for Cape conditions.

Table 15 Details of the **calibration models** used in the analysis of weekly streamflow in **Tierkloof** using Langrivier as the control.

Dependent Variable	**Model**	**Intercept (β_0)**	**Regression coefficients (β_1, β_2)**	**Adjusted R^2**	**Error d.f***
Tierkloof: total flow:	$T = \beta_0 + \beta_1.ln\,C + \beta_2(C^{\frac{1}{2}}.AW)$	-1.9516	1.3174 3.3853	0.93	727
Tierkloof: total flow:	$lnT = \beta_0 + \beta_1.ln\,C + \beta_2.AW + \beta_3.ln\,AW2$	1.045	0.5492 0.0029 0.0964	0.95	726
Tierkloof: Low flow:	$lnT = \beta_0 + \beta_1.C + \beta_2.AW + \beta_3.lnAW + \beta_4.lnAW2$	0.6297	0.1158 -0.0110 0.3169 -0.0501	0.69	124

T = streamflow (mm) from treated catchment, Tierkloof
C = streamflow (mm) from control catchment, Langrivier
AW, AW2 = antecedent wetness by two decay factors, 0.8 and 0.2 respectively
* d.f. = degrees of freedom

The total flows are rapidly reduced following afforestation (Figure 10), and peak between 16 and 20 years of tree age at levels of 9%/10% planted. However, there is a distinct diminishing of flow reductions as the trees age, and by 30 years of age the flow reductions are much smaller, being generally less than 4%/10% in the last ten years of the rotation. Relative to the general empirical curve for this site, and as for Biesievlei, the early flow reductions are under-predicted, while the later reductions are greatly over-predicted. For the Tierkloof results the asymptotic shape of the general flow reduction curve is also not appropriate and a quadratic curve would seem more appropriate (Figure 11). The low flow reductions follow much the same pattern as the total flow reductions, though there is more variability in the effect on low flows, the low flow reductions are decidedly greater being closer to the general prediction of 8.5%/10% planted (Figures 11 & 12).

Table 16 Reductions in total and low flows at **Tierkloof** catchment, Jonkershoek, 36% afforested with *Pinus radiata*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual Rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)	Low flow reduction (mm)	95% CI (mm)	Low flow reduction (%)
0	1956	1384	-18.5	19.7	-1.8	0.5	2.6	0.8
1	1957	1717	-62.3	22.7	-4.9	-3.9	2.0	-7.9
2	1958	1285	9.0	18.7	1.0	5.1	4.8	6.6
3	1959	1487	59.4	19.3	5.9	6.5	5.5	8.0
4	1960	1057	61.9	16.6	8.8	26.6	21.4	21.5
5	1961	1167	29.3	17.2	3.7	14.7	12.1	14.3
			13.1		**1.4**	**8.2**		**10.0**
6	1962	1489	-233.3	22.0	-19.1	-6.2	8.1	-6.8
7	1963	1287	67.1	17.7	8.0	15.2	6.7	17.7
8	1964	1371	181.7	17.6	21.8	10.8	3.7	38.7
9	1965	1191	159.9	17.4	19.7	29.2	5.2	36.8
10	1966	1090	175.5	17.3	22.1	30.4	4.9	39.1
			70.2		**7.8**	**15.9**		**21.9**
11	1967	1425	166.2	18.7	17.5	14.6	2.2	34.6
12	1968	1506	168.0	19.6	16.4	10.9	2.1	22.4
13	1969	923	193.3	16.2	29.2	42.2	8.4	45.8
14	1970	1405	187.9	18.8	19.6	26.2	7.1	29.9
15	1971	995	150.1	16.5	21.4	41.5	10.1	42.6
			173.1		**20.1**	**27.1**		**36.8**
16	1972	1134	228.4	16.7	31.8	55.7	27.1	41.6
17	1973	860	203.2	15.8	34.3	52.3	10.3	53.4
18	1974	1510	208.4	19.9	19.8	14.0	2.1	27.4
19	1975	1262	139.9	18.5	15.0	16.9	8.9	18.1
20	1976	1808	165.9	22.3	13.4	1.0	8.3	14.6
			189.2		**20.9**	**28.0**		**36.4**
21	1977	1686	-181.2	26.2	-12.2	13.9	18.3	11.8
22	1978	1025	150.0	16.3	22.6	28.4	5.0	36.2
23	1979	1020	160.2	17.0	21.0	22.0	3.1	32.8
24	1980	1255	203.1	17.3	25.6	20.7	2.1	42.6
25	1981	1195	171.6	17.6	20.5	26.5	6.0	31.8
			100.7		**11.1**	**22.3**		**28.2**
26	1982	1170	160.0	17.0	21.0	26.9	3.3	39.5
27	1983	1318	96.5	20.5	8.7	25.1	7.7	27.9
28	1984	1560	117.3	19.2	11.8	20.2	5.1	25.6
29	1985	1254	137.5	18.7	14.6	13.4	6.3	15.8
30	1986	1247	48.0	19.2	4.8	23.7	5.2	29.9
			111.9		**11.6**	**21.9**		**27.3**
31	1987	1268	83.0	18.7	8.8	17.8	4.3	23.8
32	1988	1384	146.9	18.1	16.6	6.3	4.3	8.4
33	1989	1222	36.6	18.1	4.1	14.4	11.1	14.4
34	1990	1318	107.4	19.9	10.2	-2.5	2.1	-4.8
35	1991	1542	138.8	20.7	12.4	0.6	2.1	1.2
			102.6		**10.5**	**7.3**		**10.4**
36	1992	1555	-11.7	20.7	-1.0	7.1	13.5	6.7
37	1993	1257	-80.3	19.8	-7.7	33.4	16.8	29.2
38	1994	1110	213.8	17.5	26.2	21.4	9.9	22.2
39	1995	1377	58.0	17.5	7.1	2.6	6.4	17.9
40	1996	1602	292.7	23.9	21.7	**16.1**		**19.4**
			94.5		**9.2**			

The reductions in low flow also show a downward trend in the later stages of the rotation, though to a lesser extent than the total flows. Part of the explanation for the large variability is a stronger negative relationship between the rainfall year and flow reductions: the smallest flow reductions are recorded in the wettest years (Table 16). This is perhaps more a reflection of the increased role of the large, unplanted, upper slopes to the water yield in these years.

Another point well illustrated by Figure 12 is the smaller relative effect of forestry in the wet season. During the wettest months of June, July and August flow reductions are large but no larger than in the autumn months while the catchment is recharging. A larger proportion of the flow from the catchment could also be produced by the upper, steeper section during this wet time of the year.

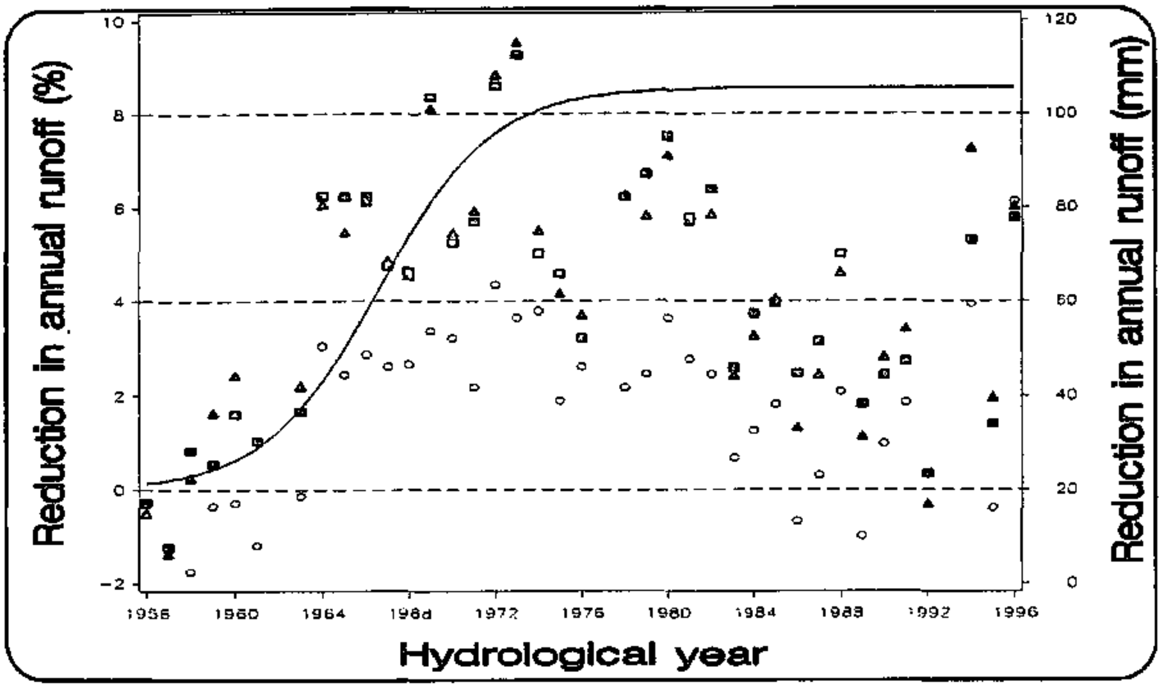


Figure 10 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Tierkloof** following 36% planting to pines in 1956, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

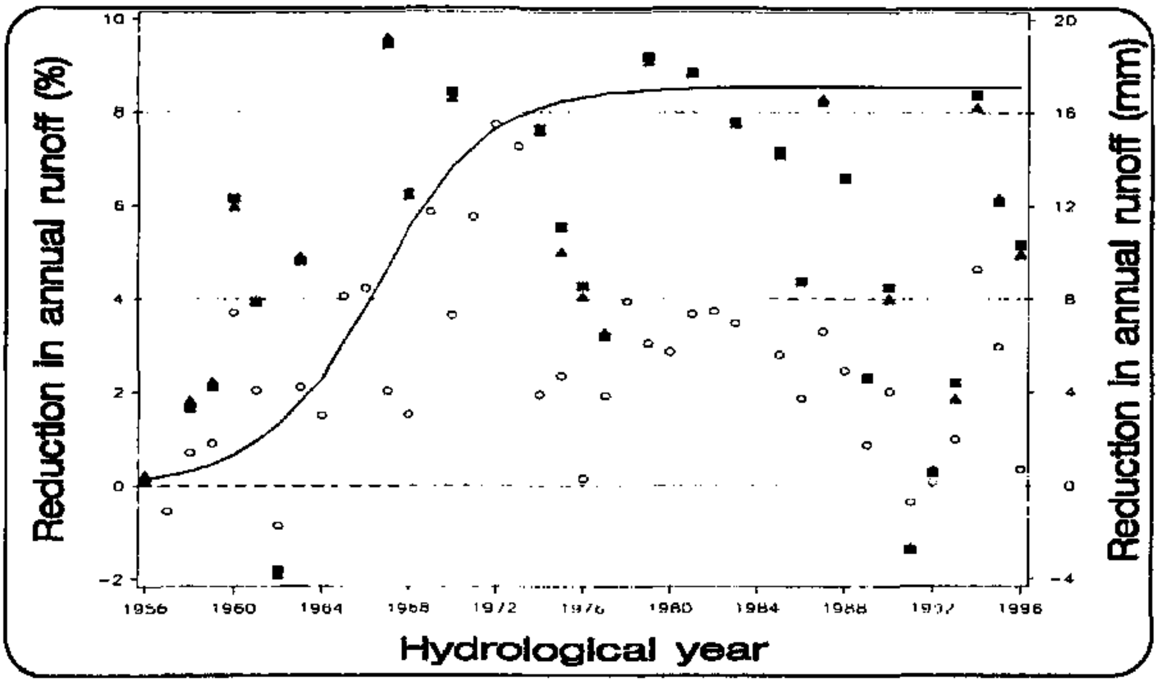


Figure 11 The relative reductions in **low flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Tierkloof** following 36% planting to pines in 1956, plotted against hydrological year.

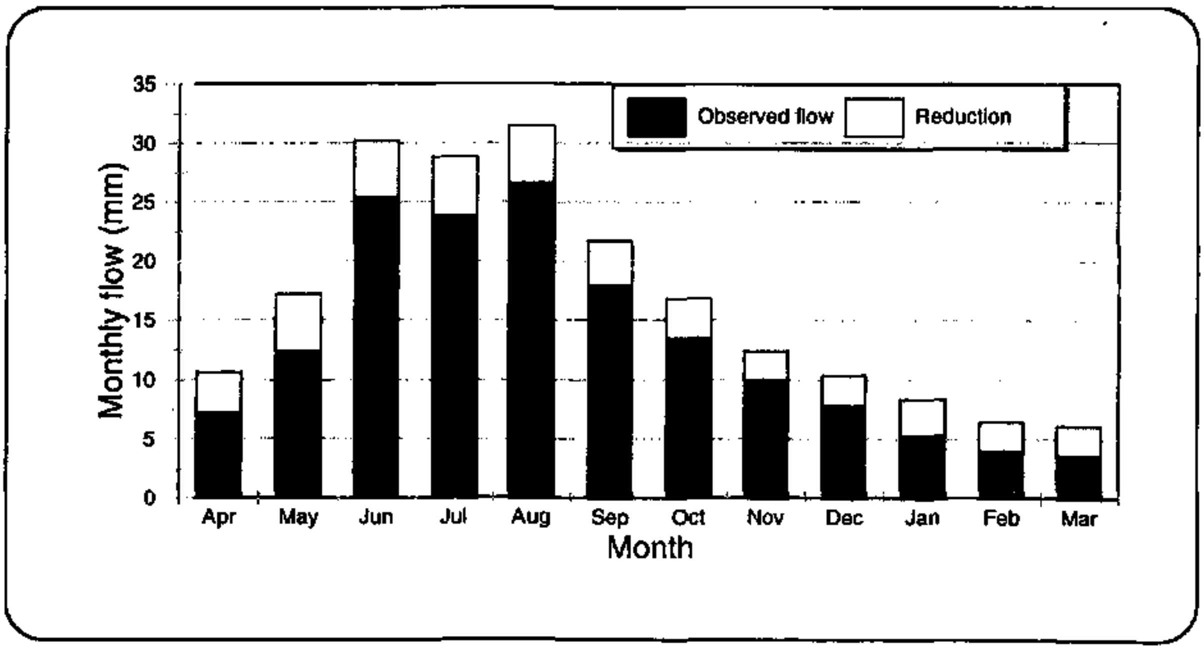


Figure 12 The mean monthly observed flows and estimated reductions as a result of afforestation in **Tierkloof** over the period 1966 to 1976 once the trees were mature.

4.9 LAMBRECHTSBOS-B: INITIAL AFFORESTATION (82% *PINUS RADIATA*, 1964)

The calibrations are fairly good for Jonkershoek (Table 17). This catchment is steep and narrow and this is perhaps the reason that it calibrates fairly well with Langrivier.

Initially there is no effect of forestry but five years after planting flow is reduced rapidly (Figure 13). This catchment is one of those on which the general models were developed and the good fit over the first twenty years is not surprising. However, beyond twenty years there is a sharp change and the latter part of the rotation had flows being reduced by around 4%/10% planted, as opposed to the expected 8.3% reduction (Figure 13). Flow reductions once the trees are mature are approximately 20 mm/10% planted. The reductions in low flow, once again, follow the same pattern as those of total flows and are greater (Figures 14 & 15). Relative to the general prediction model, the low flows reductions are under-predicted initially and over-predicted once the trees are mature (Figure 14). What is noticeable about the low flow reductions is that they comprise a large portion of the annual reductions (roughly a third; Table 18).

Table 17 Details of the **calibration models** used in the analysis of weekly streamflow in **Lambrechtsbos-B** for initial planting using Langrivier as control catchment.

Dependent Variable	Model	Intercept (β_0)	Regression coefficients (β_1, β_2)	Adjusted R^2	Error d.f*
Lambrechtsbos-B: Total flow 1	$T = \beta_0 + \beta_1.C +$ $\beta_2.AW +$ $\beta_3.(C.AW)$	-2.146958	-0.083767 0.019229 0.000338	0.88	936
Lambrechtsbos-B: Total flow 2	$\ln T = \beta_0 + \beta_1.AW +$ $\beta_2.C^{½} + \beta_3.C$	0.479742	0.002466 0.131227 -0.001912	0.93	936
Lambrechtsbos-B : Low flow 1	$T = \beta_0 + \beta_1.\ln AW +$ $\beta_2.(C.AW) + \beta_3.AW2$	-1.173414	0.003782 0.000195 0.012360	0.74	226
Lambrechtsbos-B : Low flow 2	$\ln T = \beta_0 + \beta_1.AW2 +$ $\beta_2 \log AW + \beta_3 \ln C$	-3.483726	0.0027 1.528424 0.182476	0.74	226

T = streamflow (mm) from treated catchment, Lambrechtsbos-B
C = streamflow (mm) from control catchment, Lambrechtsbos - B
AW, AW2 = antecedent wetness by two decay factors, 0.975 and 0.2 respectively
* d.f. = degrees of freedom

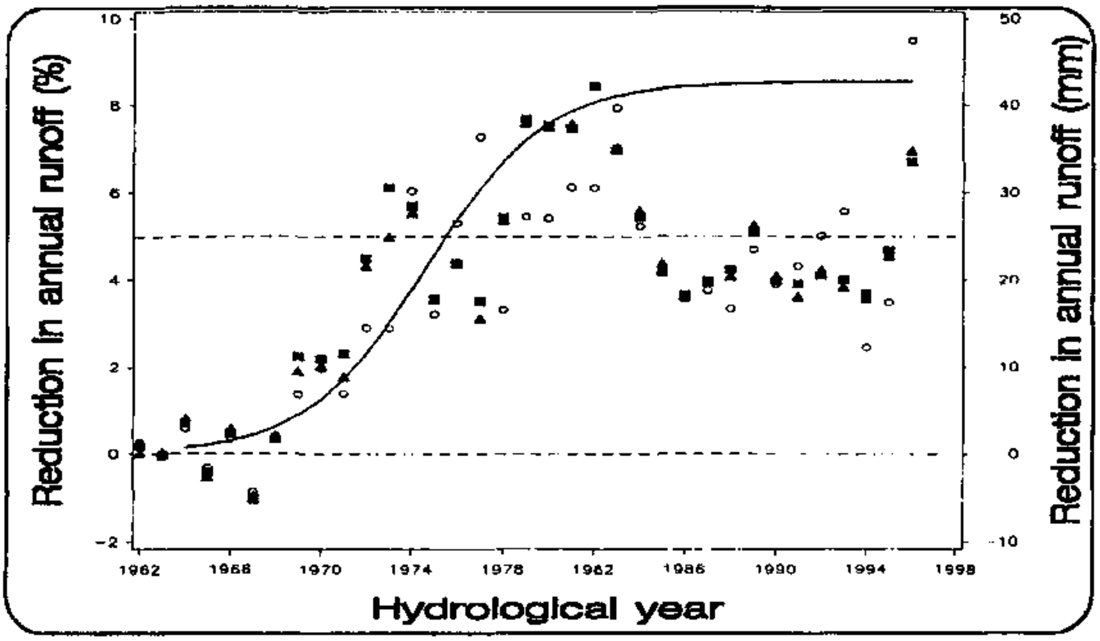


Figure 13 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Lambrechtsbos B** following 82% planting to pines in 1964, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

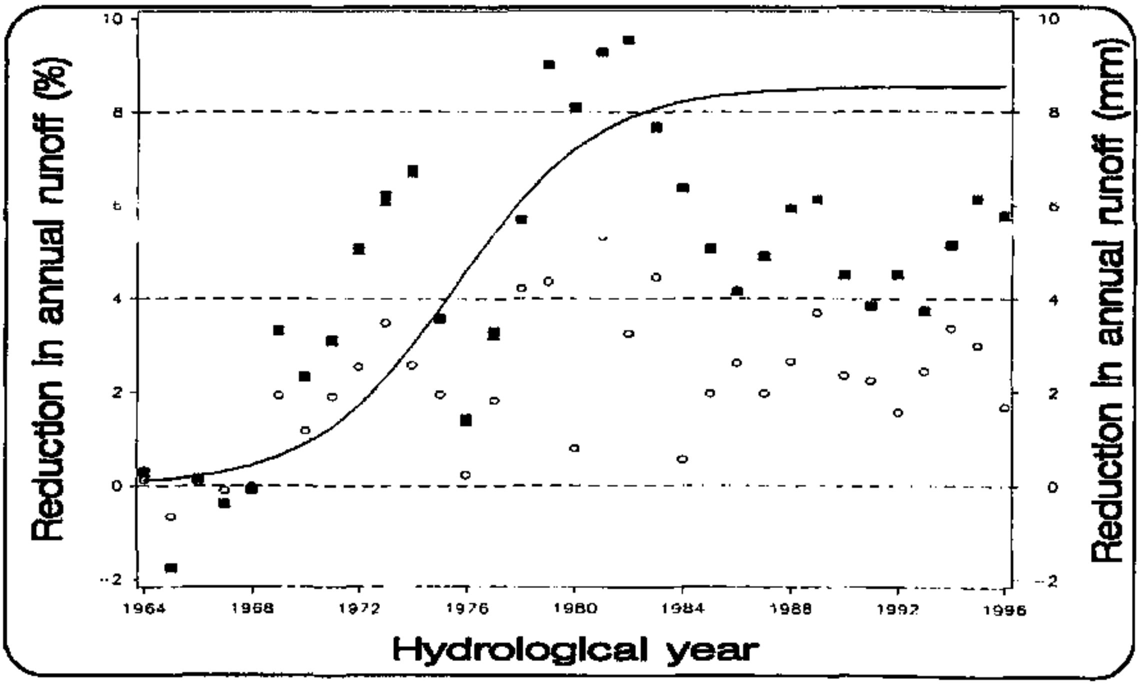


Figure 14 The relative reductions in **low flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Lambrechtsbos B** following 82% planting to pines in 1964, plotted against hydrological year.

Table 18 Reductions in total and low flows at **Lambrechtbos-B**, Jonkershoek, 82% afforested with *Pinus radiata*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)	Low flow reduction (mm)	95% CI (mm)	Low flow reduction (%)
0	1964	1198	26.5	14.1	6.6	1.0	1.4	2.8
1	1965	1005	-16.3	14.1	-4.4	-5.4	1.3	-14.3
2	1966	921	18.6	14.1	4.8	0.6	1.2	1.3
3	1967	1147	-32.7	14.2	-7.8	-0.8	1.6	-3.0
4	1968	1295	18.4	14.7	3.5	-0.1	1.8	-0.3
5	1969	826	46.1	14.0	15.7	15.8	1.4	27.2
			10.1		**2.5**	**1.9**		**4.8**
6	1970	1168	73.7	14.2	16.7	9.6	1.2	19.1
7	1971	852	41.3	14.0	14.5	15.7	1.5	25.4
8	1972	935	111.5	14.0	35.4	20.9	1.2	41.2
9	1973	747	81.4	14.1	40.9	28.5	1.4	49.7
10	1974	1291	235.4	14.6	45.4	21.1	1.3	55.1
			108.7		**30.9**	**19.2**		**36.8**
11	1975	1055	130.3	14.3	29.1	16.0	1.3	29.4
12	1976	1490	219.7	15.2	36.1	1.9	2.3	11.3
13	1977	1522	252.5	20.2	25.5	14.9	1.4	26.4
14	1978	927	133.1	14.0	44.0	34.6	2.2	46.7
15	1979	902	217.5	14.0	62.3	35.8	1.2	73.9
			190.6		**35.3**	**20.6**		**41.2**
16	1980	1158	219.0	14.0	61.5	6.6	2.8	66.4
17	1981	1034	260.2	14.2	62.1	43.6	1.4	76.3
18	1982	1079	252.2	14.0	69.4	26.7	1.4	78.4
19	1983	1139	331.8	15.0	57.7	36.5	1.4	63.1
20	1984	1365	224.9	14.5	45.8	4.6	2.9	52.2
			257.6		**58.4**	**23.6**		**70.5**
21	1985	1072	186.6	14.6	36.0	16.2	1.3	41.7
22	1986	1111	143.4	14.4	29.7	21.6	1.6	34.2
23	1987	1126	152.4	14.4	32.4	16.2	1.3	40.3
24	1988	1216	129.3	14.1	33.5	21.8	1.2	48.8
25	1989	1038	202.1	14.3	43.2	30.3	1.5	50.3
			162.8		**35.0**	**21.2**		**43.1**
26	1990	1069	167.6	14.5	33.6	19.3	1.3	37.1
27	1991	1273	158.4	14.7	29.7	18.4	1.4	31.6
28	1992	1334	214.4	15.3	34.6	12.8	1.4	37.1
29	1993	1279	214.5	15.9	31.4	20.1	1.7	30.9
30	1994	869	95.7	14.0	29.3	27.7	1.7	42.3
			170.1		**32.0**	**19.7**		**35.7**
31	1995	1129	136.6	14.0	37.4	24.6	1.2	50.3
32	1996	1395	422.7	16.5	57.0	13.8	1.6	47.3
			279.6		**50.5**	**19.2**		**49.1**

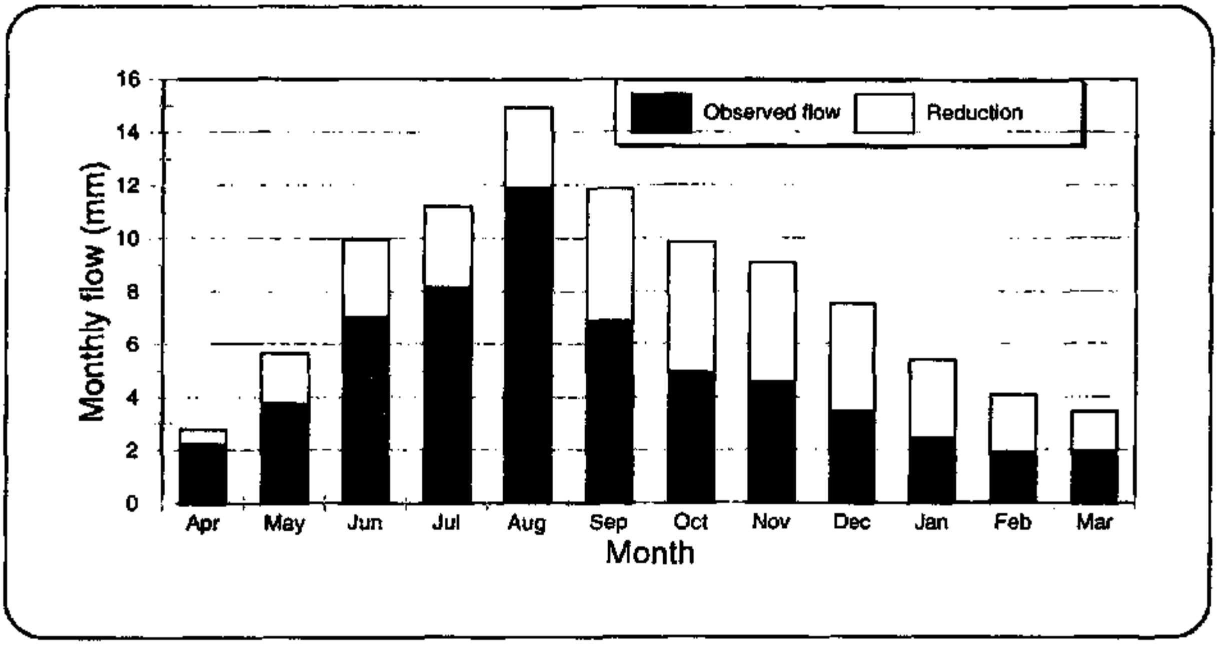


Figure 15 The mean monthly observed flows and estimated reductions as a result of afforestation in **Lambrechtsbos** B over the period 1973 to 1981 once the trees were mature.

4.10 LAMBRECHTSBOS-A: INITIAL AFFORESTATION (89% *PINUS RADIATA*, 1972)

As for Lambrechtsbos-B, the calibration models for Lambrechtsbos-A are fairly good by Jonkershoek standards (Table 19). The catchment was only planted in 1972 and closed because of financial constraints in 1991, so a mere twenty years of post-treatment observations are available.

Flow reductions peaked in absolute and relative terms earlier in the rotation than for any Jonkershoek catchment: between eight and twelve years of age the trees had the largest impact on streamflow of 7.5 to 8%/10% which was followed by a clear decline in influence by 20 years of age (Figure 16; Table 19). Absolute reductions are highly variable: peaking at 44 mm/10% in the eleventh year but going as low as 20 mm/10% in the dry hydrological year of 1988 (Figure 16).

The effects of afforestation on low flows agreed with the observations in the other Jonkershoek catchments. Reductions are more variable from year to year, and are greater than the relative reductions in total flow (Figure 17; Table 20), but the overall pattern over the length of the rotation is the same. The effect of forestry on low flows is clearly greater than it is in the wetter months as can be seen in Figure 18, where the effects of forestry, though remarkably consistent throughout the year, are relatively smallest in the wettest month of August. In absolute terms the low flow reductions are also reduced in the driest months (January to April) perhaps indicating some limitation caused by a lesser availability of water.

Table 19 Details of the **calibration** models used in the analysis of weekly streamflow in **Lambrechtsbos-A** for initial planting using Langrivier as control catchment.

Dependent Variable	**Model**	**Intercept (β_0)**	**Regression coefficients (β_1, β_2)**	**Adjusted R^2**	**Error d.f***
Lambrechtsbos-A: Total flow 1	$T = \beta_0 + \beta_1 C +$ $\beta_2(C^{½}.AW) + \beta_3.AW$	-4.766883	-0.149891 0.000256 0.018906	0.88	1353
Lambrechtsbos-A: Total flow 2	$\ln T = \beta_0 +$ $\beta_1.(C^{½}.AW) + \beta_2.C^{½}$ $+ \beta_3.AW$	0.715683	0.000002552 0.019195 0.002056	0.9	1353
Lambrechtsbos-A: Low flow 1	$T = \beta_0 + \beta_1.\ln AW +$ $\beta_2. AW2 + \beta_3.\ln C$	-2.412167	0.010888 0.026722 -0.799936	0.71	325
Lambrechtsbos-A: Low flow 2	$\ln T = \beta_0 +$ $\beta_1.\log.AW + \beta_2.C +$ $\beta_3 \ln AW$	-6.197327	2.101474 -0.017415 0.491051	0.73	325

T = streamflow (mm) from treated catchment, Lambrechtsbos-A
C = streamflow (mm) *from control catchment*, Langrivier
AW, AW2 = antecedent wetness by two decay factors, 0.97 and 0.2 respectively.
* d.f. = degrees of freedom

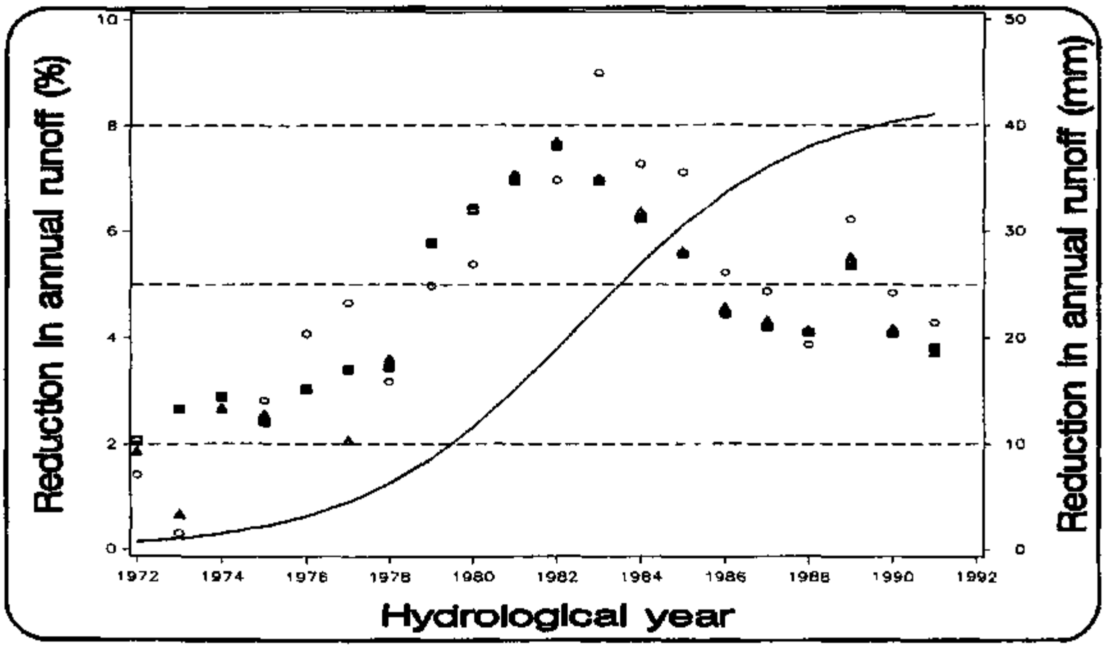


Figure 16 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Lambrechtsbos A** following 89% planting to pines in 1972, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

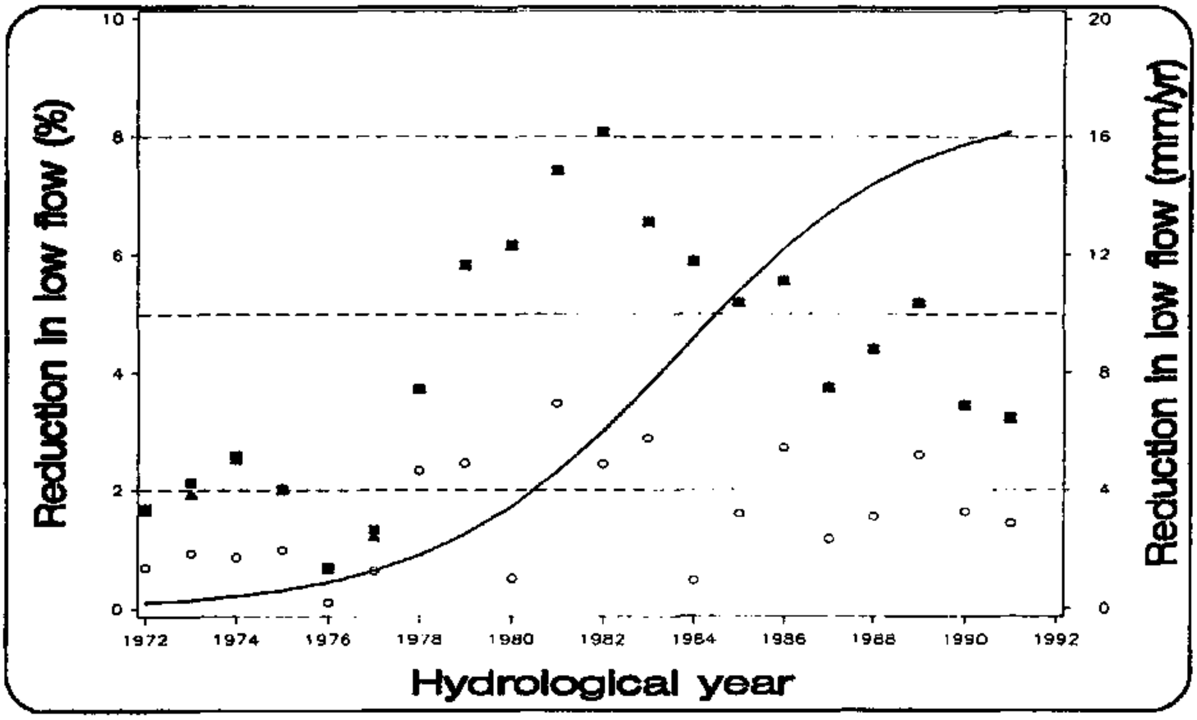


Figure 17 The relative reductions in **low flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Lambrechtsbos A** following 89 % planting to pines in 1972, plotted against hydrological year.

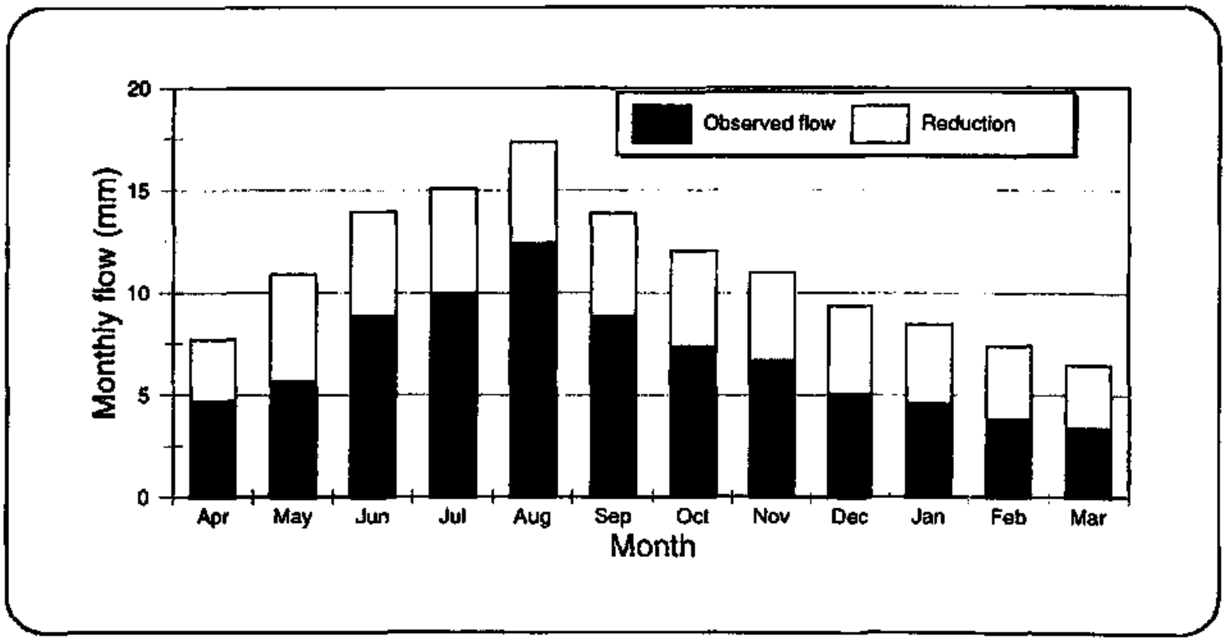


Figure 18 The mean monthly observed flows and estimated reductions as a result of afforestation in Lambrechtsbos A over the period 1977 to 1981 once the trees were mature.

Table 20 Reductions in total and low flows at **Lambrechtsbos A** catchment, 89% afforested with *Pinus radiata*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual Rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)	Low flow reduction (mm)	95% CI (mm)	Low flow reduction (%)
0	1972	935	62.9	9.1	16.6	16.6	1.5	17.2
1	1973	747	13.4	11.0	5.9	15.3	1.6	22.5
2	1974	1291	127.6	8.6	23.8	17.5	1.5	18.0
3	1975	1055	125.2	8.7	22.8	1.8	4.3	6.0
4	1976	1490	181.0	9.5	26.9	11.2	1.7	10.7
			102.0		**21.5**	**12.5**		**15.7**
5	1977	1522	206.9	20.4	18.4	41.5	3.0	33.2
6	1978	927	140.8	8.8	32.0	43.7	1.3	51.9
7	1979	902	221.4	8.8	51.6	9.0	6.0	54.8
8	1980	1158	239.1	8.9	56.9	61.9	1.4	66.2
9	1981	1034	313.9	8.6	62.9	43.5	1.9	72.0
			224.4		**38.5**	**39.9**		**52.6**
10	1982	1079	309.6	8.7	68.4	51.3	1.4	58.4
11	1984	1365	323.2	8.7	56.6	28.4	1.9	46.3
12	1985	1072	316.4	9.1	50.0	48.5	1.5	49.6
13	1986	1111	232.2	8.7	40.6	20.9	1.8	33.5
14	1987	1126	216.5	8.7	38.5	27.5	1.6	39.3
			279.6		**50.1**	**35.3**		**46.6**
15	1988	1216	172.0	8.7	36.9	46.1	1.6	46.3
16	1989	1038	276.9	8.7	49.1	29.0	1.4	30.8
17	1990	1069	215.4	8.8	37.1	25.5	1.4	28.7
18	1991	1273	190.4	46.4	33.1	54.5		**28.7**
			213.7		**53.0**	**38.8**		

4.11 CATHEDRAL PEAK II: INITIAL AFFORESTATION (75% *PINUS PATULA*, 1951)

The calibration models at Cathedral Peak are notably better for CIII than for CII which is steeper, higher and further away from the control. Nonetheless, all the total flow models are good (adjusted $R^2 > 0.93$). As in Jonkershoek, the low flow models are generally weaker than the total flow models (adjusted R^2 0.84 to 0.88; Table 21).

Table 21 Details of the **calibration models** used in the analysis of daily streamflow for **Catchment II, Cathedral Peak** using (Catchment IV as the control).

Dependent Variable	Model	Intercept (β_0)	Regression Coefficients (β_1)	Adjusted R^2	Error d.f*
Cathedral Peak II Total flow 1	$\ln T = \beta_0 + \beta_1.\ln C$	0.0198	1.0369	0.94	259
Cathedral Peak II Total flow 2	$T = \beta_0 + \beta_1.C$	-0.5074	1.2261	0.93	259
Cathedral Peak II Low flow 1	$\ln T = \beta_0 + \beta AW + \beta^{\frac{1}{2}}LAW + \beta C^2$	5.4184	0.0104 -1.148 0.0210	0.8436	80
Cathedral Peak II Low flow 2	$T = \beta_0 + \beta_1 AW + \beta_2 LAW + \beta_3 CIVSQ$	35.4495	0.07575 -8.9227 0.1069	0.8802	80

T = streamflow (mm) from treated catchment (II)
C = streamflow (mm) from control catchment (IV)
* d.f. = degrees of freedom

The first six years of the rotation are not significantly affected, but thereafter flow is reduced strongly to peak reductions at 20 years (Figure 19). Also apparent is the excellent fit of the general empirical model to these independent data over the initial 20 years. Despite the naturally high yield of these catchments the mature pines caused very large percentage flow reductions, peaking at over 8%/10% of catchment area planted and over 60 mm/10% in mature, healthy trees (Table 22). The fall-off in reductions after 1970 (Figure 19) has been attributed to an outbreak of *Euproctis terminalis* larvae that caused an estimated 25% defoliation of the trees in the pine plantation, and there is a return to previous levels of relative flow reduction as the pines recovered full foliage toward 1980 (29 & 30 year old trees).

But the absolute flow reductions are little different over this period when the trees were between 20 and 30 years old. Thus, the lower relative flow reductions could also be attributed to the above average rainfall in those years, and that the effect of the trees was climatically limited (i.e limited by atmospheric demand).

Low flows were reduced more than total flows, and this is apparent in both a comparison of Figures 19 and 20, and in Figure 21. As the catchment wets up toward late summer there is a lower relative effect on flows, but as early as May it is clear that flows were more severely affected than in the wetter months (Figure 21).

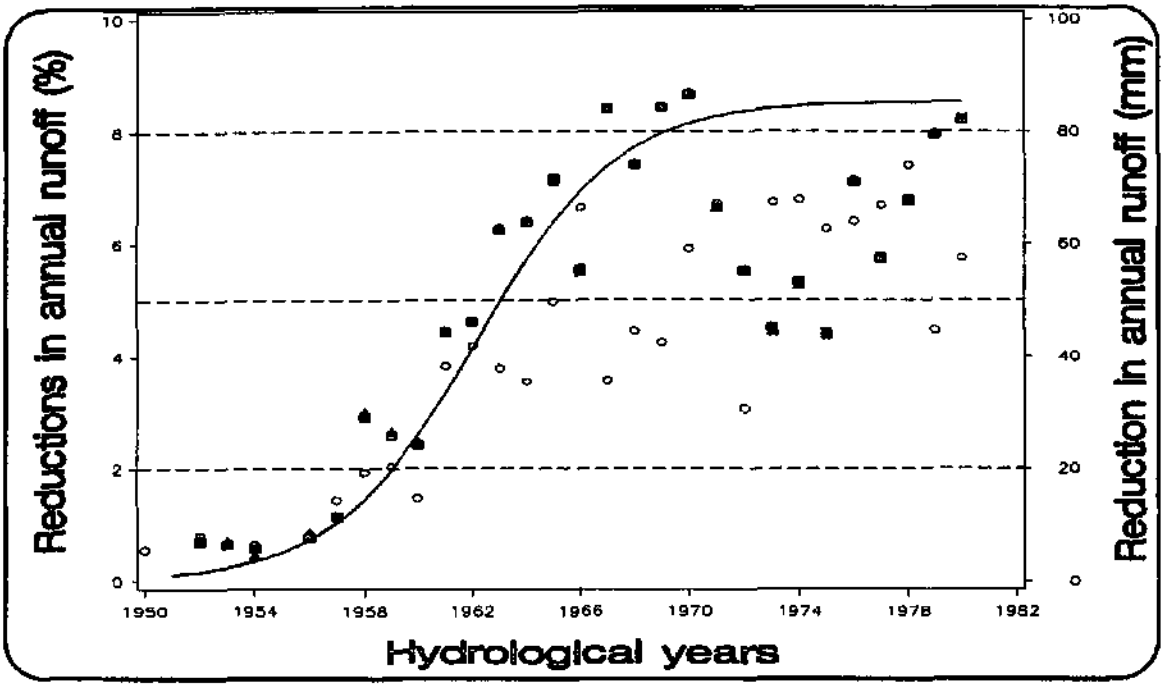


Figure 19 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Catchment II, Cathedral Peak** following 75% planting to pines in 1951, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

Table 22 Reductions in **total and low flows** at **Catchment II, Cathedral Peak**, 75% afforested with *Pinus patula*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)	Low flow reduction (mm)	95% CI (mm)	Low flow reduction (%)
0	1951	1366	-120.0	37.5	-18.3	-10.1	12.6	-8.7
1	1952	1524	61.1	39.6	5.6	-0.0	3.9	-0.1
2	1953	1520	52.2	38.9	5.3	3.3	3.6	6.5
3	1954	1856	49.1	42.2	3.5	-1.5	3.6	-3.6
4	1955	1342	-52.9	37.8	-7.1	0.5	3.7	1.0
5	1956	1921	62.9	38.9	6.5	0.0	4.6	0.2
			8.8		**0.9**	**-1.3**		**-2.5**
6	1957	1674	108.0	40.8	8.6	0.5	4.0	1.8
7	1958	1451	144.9	37.4	22.5	4.1	4.0	14.0
8	1959	1437	152.6	37.9	19.9	9.3	3.6	24.1
9	1960	1314	110.7	37.3	18.7	17.7	3.7	32.6
10	1961	1350	287.1	38.3	33.5	17.7	3.6	34.9
			160.7		**19.5**	**9.9**		**24.5**
11	1962	1532	313.5	38.5	34.7	24.6	3.6	46.7
12	1963	1459	284.3	37.3	47.2	18.9	3.6	47.9
13	1964	1185	266.2	37.2	48.1	16.8	3.6	45.5
14	1965	1276	373.1	37.6	53.6	33.1	3.8	57.2
15	1966	1785	498.7	40.4	41.4	40.3	4.2	62.6
			347.2		**43.8**	**26.7**		**53.2**
16	1967	1082	267.2	37.0	63.0	31.3	3.6	62.4
17	1968	1332	333.5	37.3	55.8	31.5	3.6	62.7
18	1969	1151	318.1	37.1	63.3	38.6	3.7	69.7
19	1970	1088	443.5	37.6	65.2	9.8	5.2	68.7
20	1971	1518	504.0	39.1	49.8	14.9	3.9	48.1
			373.3		**58.0**	**25.2**		**62.7**
21	1972	1465	229.5	37.2	41.5	58.4	9.8	56.0
22	1973	1905	505.7	43.1	33.4	9.2	4.4	40.0
23	1974	1910	509.0	41.1	39.5	19.7	3.5	46.9
24	1975	2120	470.0	42.3	32.9	19.7	3.6	49.4
25	1976	1535	479.7	38.5	53.5	13.0	4.1	48.6
			438.8		**38.6**	**24.0**		**50.9**
26	1977	1849	501.5	40.1	43.1	21.0	3.5	47.1
27	1978	1837	555.2	39.6	50.8	13.1	4.3	53.8
28	1979	1293	335.1	37.2	59.8	23.3	3.6	60.1
29	1980	1362	431.1	37.6	61.7	58.3	6.7	66.9
			455.7		**51.9**	**28.9**		**59.4**

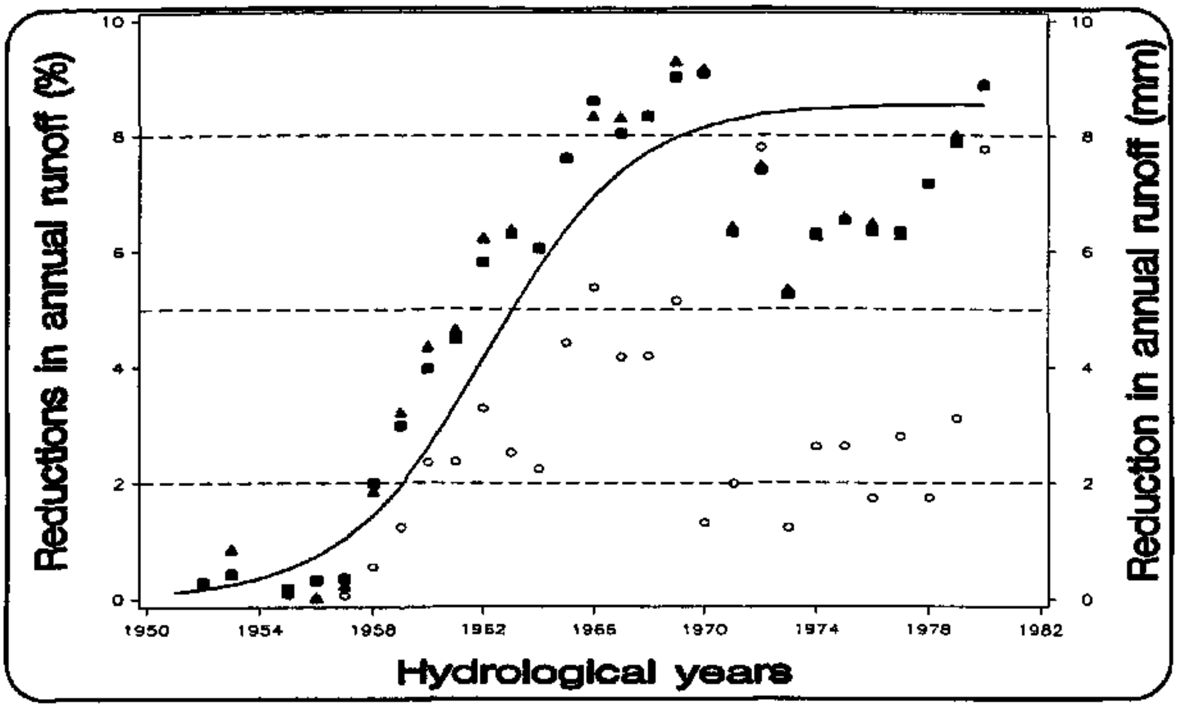


Figure 20 The relative reductions in **low flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Catchment II, Cathedral Peak** following 75% planting to pines in 1951, plotted against hydrological year. Reductions are standardised to a 10% level of planting.

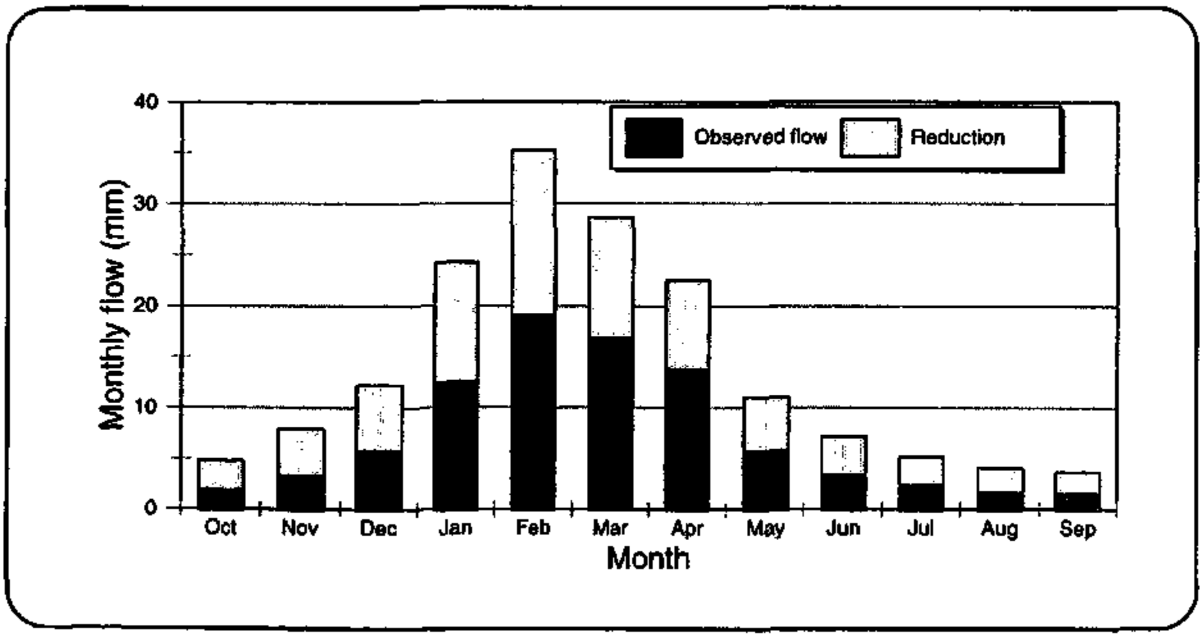


Figure 21 The mean monthly observed flows and estimated reductions as a result of afforestation in **Catchment II, Cathedral Peak** over the period 1960 to 1971 once the trees were mature.

4.12 CATHEDRAL PEAK III: INITIAL AFFORESTATION (86% *PINUS PATULA*, 1958)

The calibration models based on the adjacent Catchment IV are tight and simple, though decidedly weaker for the low flows (Table 23).

Streamflows are, if anything, higher in the early part of the rotation than before planting, possibly a reflection of a fire soon after the initial planting that necessitated the replanting of half the plantation (Table 24). The streamflow was rapidly reduced after 1966 only reaching peak reductions just before another fire (that terminated the experiment) in 1981 (Figures 22 and 23). As in CII relative flow reductions in the early 1970's coincided with the outbreak of defoliating insects. However, absolute reductions show little sign of declining and, again as in CII, the relative reductions are more probably the result of a particularly wet cycle over this period.

As in Catchment II it is clear that dry season flows suffer greater percentage reductions than the wettest months (Figure 24), though absolute reductions are much greater in summer. Flow reductions in early summer, though, are especially high in both relative and absolute terms, presumably while the catchments are being recharged after the seasonal drought.

Table 23 Details of the **calibration models** used in the analysis of daily streamflow for **Catchment III, Cathedral Peak**, using (catchment IV as the control).

Dependent Variable	**Model**	**Intercept (β_0)**	***Regression* Coefficients (β_1)**	**Adjusted R^2**	**Error d.f***
Cathedral Peak III Total flow 1	$T = \beta_0 + \beta_1.C +$ $\beta_2 AW$	-0.1728	0.9787 0.002764	0.985	436
Cathedral Peak III Total flow 2	$\ln T = \beta_0 + \beta_1.\ln C$	0.0279	0.9963	0.9815	437
Cathedral Peak III Total flow 3	$T = \beta_0 + \beta_1.C$	0.30605	1.0003	0.985	437
Cathedral Peak III Low flow 1	LQCIII = LQCIV	0.1228	0.9278	0.8838	99
Cathedral Peak III Low flow 2	QCIII = QCIV	0.2548	0.9465	0.8671	99

T = streamflow (mm) from treated catchment (III)
C = streamflow (mm) from control catchment (IV)
* d.f. = degrees of freedom

Table 24 Reductions in **total and low flows** at **Catchment III, Cathedral Peak**, 86% afforested with *Pinus patula*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	**Hydrological years**	**Annual rainfall (mm)**	**Total flow reduction (mm)**	**95% CI (mm)**	**Total flow reduction (%)**	**Low flow reduction (mm)**	**95% CI (mm)**	**Low flow reduction (%)**
0	1958	1441	-13.1	15.0	-2.3	0.3	1.2	0.8
1	1959	1467	-81.0	15.2	-12.2	-2.9	0.5	-7.5
2	1960	1444	-86.7	14.9	-16.6	-1.7	0.6	-3.4
3	1961	1415	-61.1	15.4	-8.3	-5.4	0.7	-10.7
4	1962	1473	-43.2	15.5	-5.6	-0.4	0.5	-0.8
5	1963	1494	-4.2	15.0	-0.8	2.0	0.5	4.9
			-48.2		**-7.6**	**-1.4**		**-3.2**
6	1964	1328	-37.8	14.9	-7.7	-3.4	0.5	-8.7
7	1965	1284	-20.2	15.1	-3.3	0.5	1.1	0.8
8	1966	1744	117.7	16.2	11.5	5.6	0.5	12.4
9	1967	1189	113.5	14.7	29.6	13.0	0.5	26.6
10	1968	1511	118.6	15.0	22.6	11.9	0.5	25.7
			58.4		**9.7**	**5.5**		**11.7**
11	1969	1298	160.8	14.8	35.9	17.4	0.7	34.0
12	1970	1252	320.7	15.1	54.1	7.5	4.0	49.4
13	1971	1722	368.4	15.7	42.7	13.5	0.9	39.7
14	1972	1407	240.0	14.9	49.1	26.7	3.0	39.1
15	1973	1828	315.6	17.1	24.8	9.1	2.1	36.6
			281.1		**38.4**	**14.8**		**38.4**
16	1974	1865	387.0	16.4	35.6	19.2	0.4	43.1
17	1975	1990	408.3	16.8	34.0	16.3	0.6	43.3
18	1976	1556	459.9	15.5	59.9	15.3	1.5	53.3
19	1977	1853	452.4	16.1	45.9	22.5	0.5	47.0
20	1978	1690	515.2	15.9	55.4	11.0	2.3	47.5
			444.5		**44.7**	**16.9**		**46.3**
21	1979	1296	351.1	14.9	71.0	26.1	0.5	65.9
22	1980	1322	271.2	15.1	44.6	35.9	4.9	47.0
			311.1		**56.5**	**31.0**		**53.4**

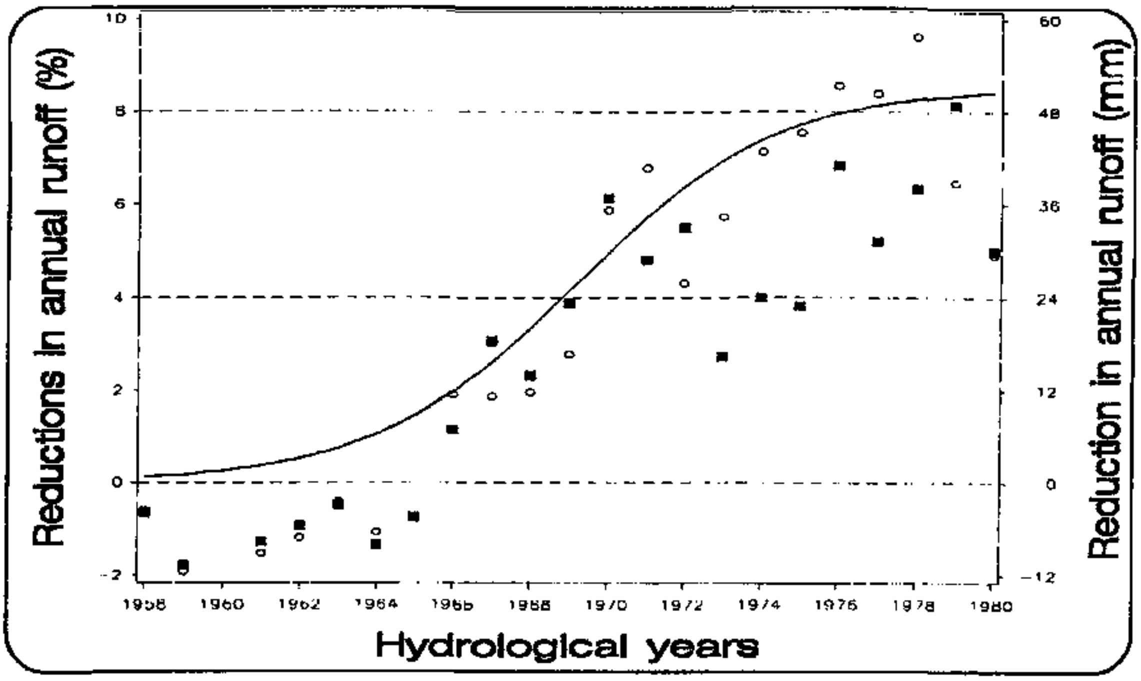


Figure 22 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Catchment III, Cathedral Peak** following 86% planting to pines in 1958, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

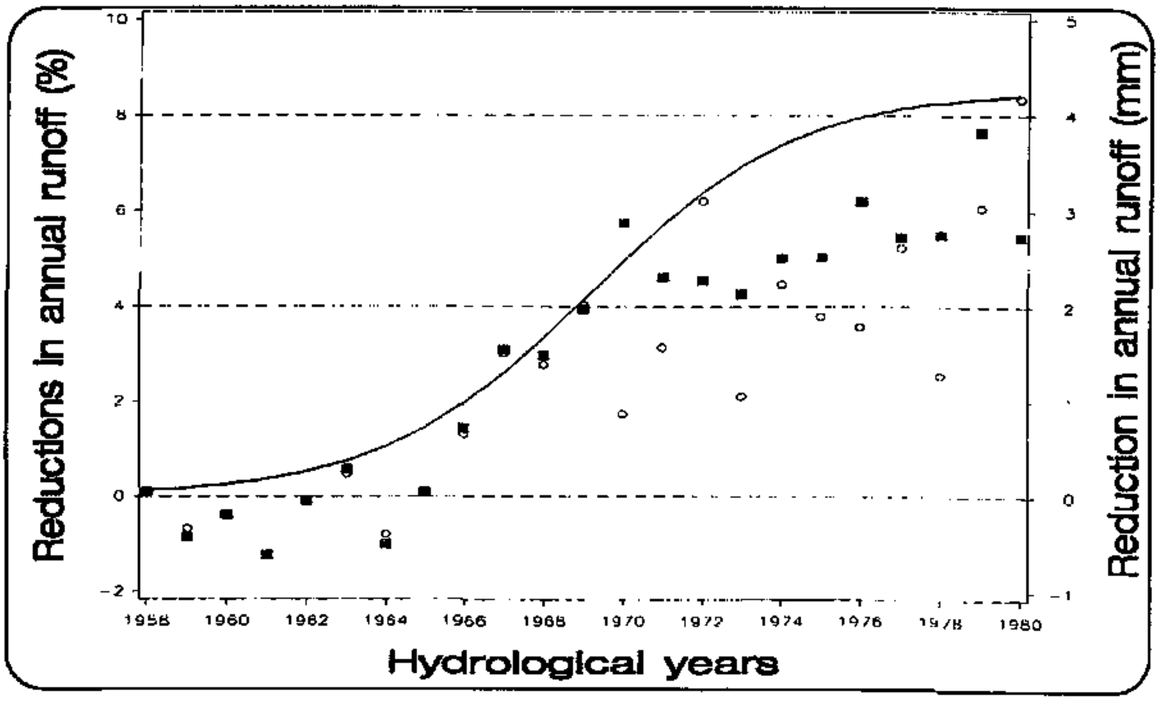


Figure 23 The relative reductions in **low flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Catchment III, Cathedral Peak** following 86% planting to pines in 1958, plotted against hydrological year. Reductions are standardised to a 10% level of planting.

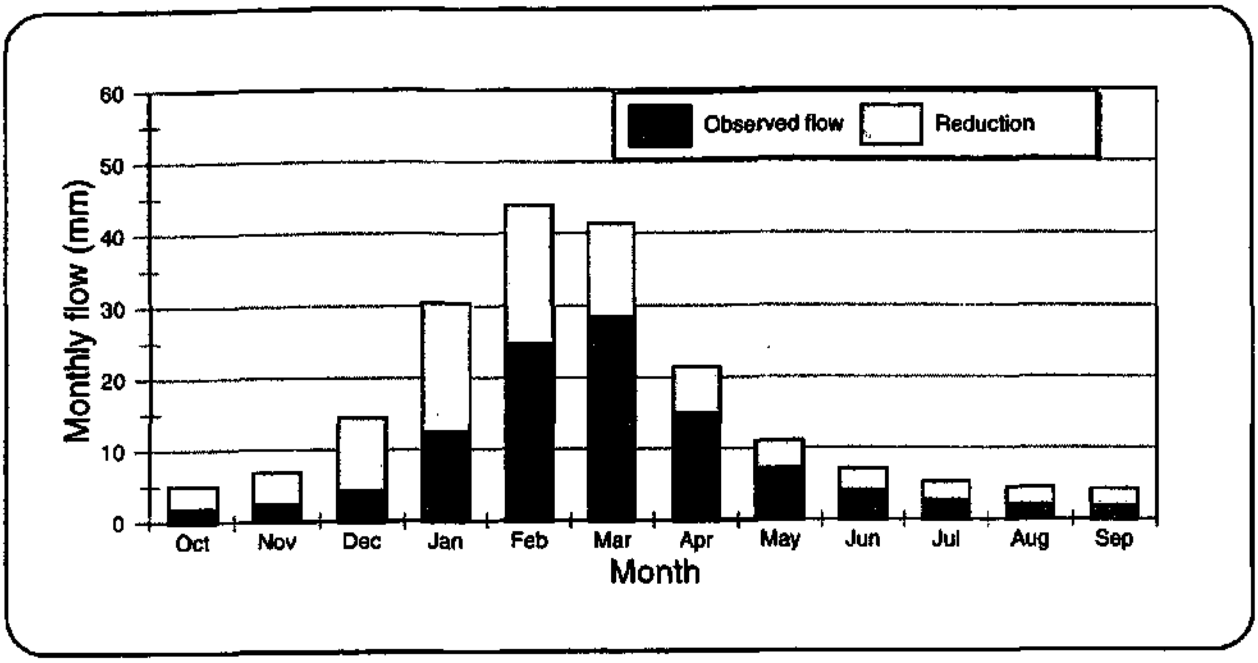


Figure 24 The mean monthly observed flows and estimated reductions as a result of afforestation in **Catchment III, Cathedral Peak** over the period 1970 to 1981 once the trees were mature.

4.13 MOKOBULAAN A: INITIAL AFFORESTATION (~97% *EUCALYPTUS GRANDIS* 1969)

At Mokobulaan it is the low flow that correlates well between the treatment and control catchments rather than the total flows, though all calibrations are good (R^2 >0.88; Table 26). Within nine years of planting eucalypts the Mokobulaan A stream was dry (Figure 25). Dry season flows dried up roughly two years ahead of wet season flow (Scott and Lesch, 1997). A heavy thinning of the trees early in the rotation had no measurable effect on streamflow that continue to decrease. The plantation in the catchment was clearfelled in 1985, at 16 years of age, but streamflow returned only five years later, and was still depressed (Table 25), despite the continued suppression of re-growing eucalypt coppice, in 1992.

This result was not really surprising as the catchment had a naturally low yield and had been fully afforested. However, it is notable in that the result demonstrated for the first time that a crop could dry up a stream completely, and that some very large and intense rainstorms did not produce streamflow even after the trees had been clearfelled. These results are an important contribution to the understanding of the flow paths and flow generating mechanisms in these humid catchments with highly permeable and deeply weathered soils. The dry season flow was reduced sooner and to a greater extent than total flow, but the desiccation followed the same pattern.

Table 25 Reductions in **total flows** at **Catchment A, Mokobulaan**, 97% afforested with *Eucalyptus grandis*. The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	Mean reduction (mm)	Total flow reduction (%)	Mean reduction (%)
0	1969	932	-6.8		-5.8	
1	1970	1192	-18.5		-14.4	
2	1971	1526	29.9		17.0	
3	1972	1207	211.7		40.5	
4	1974	1318	210.1		79.9	
5	1975	1144	423.3		81.5	
				141.6		**49.2**
6	1976	1492	361.3		93.9	
7	1977	1228	470.4		88.4	
8	1978	1233	323.5		98.7	
9	1979	1027	471.0		97.2	
10	1980	1047	147.1		100.0	
				354.7		**94.5**
11	1981	1152	173.7		99.5	
12	1982	906	195.5		100.0	
13	1983	1313	151.3		100.0	
14	1984	941	41.1		100.0	
15	1985	1144	134.1		100.0	
				139.2		**99.9**
16	1986	1165	112.6		100.0	
17	1987	1181	97.5		100.0	
18	1988	942	57.6		100.0	
19	1989	1056	99.4		100.0	
20	1990	1341	160.4		100.0	
				105.5		**100.0**
21	1991		208.1		96.2	
22	1992		94.9		31.7	
				151.5		**58.7**

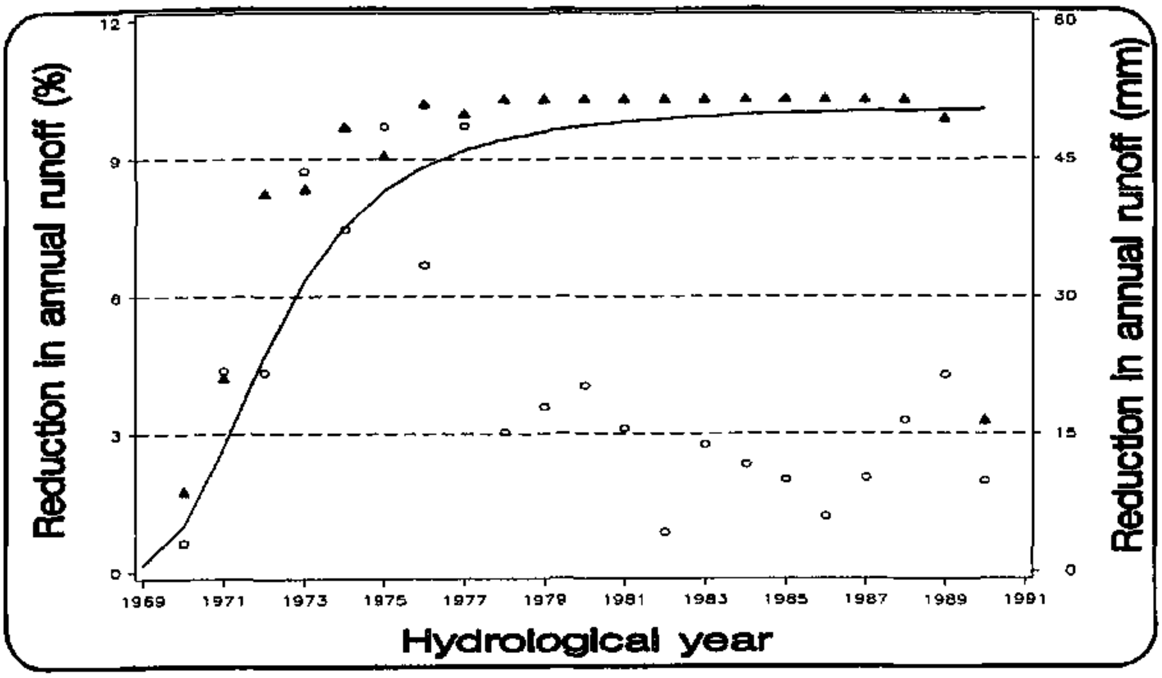


Figure 25 The relative reductions in **total flow (▲)** estimated by two different calibration models and absolute reductions (open circles) in **Catchment A, Mokobulaan** following 97% planting to eucalypts in 1969, and felling 1985. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

4.14 MOKOBULAAN B: INITIAL AFFORESTATION (~95% *PINUS PATULA*, 1971)

As had happened in Mokobulaan A, this catchment dried up quickly after planting, it being completely dry eleven years after planting (Figure 26 & Table 27). Scott and Lesch (1997) did an analysis of the Catchments in 1997. The calibration models used are shown in Table 26. As was the case in Mokobulaan A, a heavy thinning early in the rotation did not obviously slow the progressive desiccation of the catchments. The pine plantation was clearfelled between March and November 1996 and an attempt has been made to re-vegetate the catchment to grass. During 1996 the stream flowed following heavy rains, but did not flow through the weir because of a crack in the wall. This crack was fixed in December 1996. But the stream stayed dry for 2 years after felling and flow has returned intermittently in 1998 and then only during periods of heavy rainfall.

Table 26 Details of the **calibration models** used in the analysis of the monthly streamflow data sets of **Catchment A** and **Catchment B, Mokobulaan.**

Dependent Variable	Model	Intercept (β_0)	Regression coefficients	R^2
Annual streamflow in catchment A	$T = \beta_0 + \beta_1 C + \beta_2 AW$	-4.948	1.363 0.019	0.88
Dry season streamflow in catchment A	$T = \beta_0 + \beta_1 C$	1.332	1.507	0.95
Annual streamflow in catchment B	$T = \beta_0 + \beta_1 C + \beta_2 AW$	1.685	0.862 0.013	0.89
Dry season streamflow in catchment B	$T = \beta_0 + \beta_1 C$	5.586	1.106	0.93

T = streamflow (mm) from treated catchment (A, B)
C = corresponding streamflow (mm) from control catchment (C)
AW = antecedent wetness index, where monthly decay factor is 0.8
$\beta_0 - \beta_2$ = fitted regression coefficients

The dry season flow was reduced sooner and to a greater extent than total flow, but the desiccation followed the same pattern.

The slow response of the two Mokobulaan catchments to clearfelling indicates that the full effect of the plantations was not measured during the rotation. Excess rainfall after the clearfelling must have been going into recharge of the desiccated soil water stores.

Table 27 Reductions in **total flows** at **Catchment B, Mokobulaan,** 95% afforested with *Pinus patula.* The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold.

Tree age (yrs)	Hydrological years	Annual rainfall (mm)	Total flow reduction (mm)	Mean reduction (mm)	Total flow reduction (%)	Mean reduction (%)
0	1971	1490	2.3		1.3	
1	1972	1154	-21.1		-5.4	
2	1973	1295	2.2		1.0	
3	1974	1158	-4.6		-1.2	
4	1975	1488	98.6		32.2	
5	1976	1301	103.7		25.9	
				30.2		**9.6**
6	1977	1265	142.8		52.3	
7	1978	1085	160.6		43.5	
8	1979	1090	108.0		68.7	
9	1980	1266	141.6		79.5	
10	1981	938	144.5		75.3	
				139.5		**59.7**
11	1982	787	140.7		88.0	
12	1983	1406	87.7		100.0	
13	1984	1033	154.4		100.0	
14	1985	1228	141.1		100.0	
15	1986	1162	130.2		100.0	
				130.8		**97.1**
16	1987	1294	101.2		100.0	
17	1988	1045	133.5		100.0	
18	1989	1169	169.1		100.0	
19	1990	1363	203.9		100.0	
20	1991	555	257.0		100.0	
				172.9		**100**

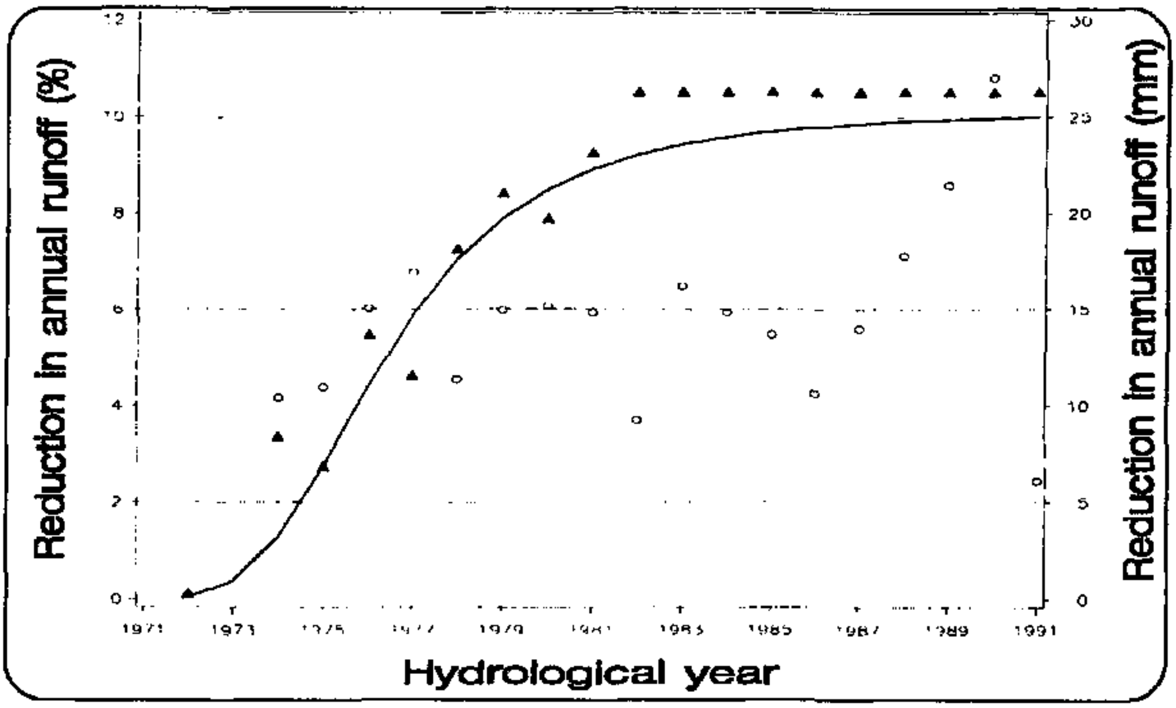


Figure 26 The relative reductions in **total flow** (▲) and absolute reductions (open circles) in **Catchment B** , **Mokobulaan** following 92% planting to pines in 1971, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

4.15 WESTFALIA D: INITIAL AFFORESTATION (83% *EUCALYPTUS GRANDIS*, 1983)

Excellent total flow calibration models were developed based on the control catchment, Westfalia B, over a long pre-treatment period while both catchments were under native evergreen forest and scrub forest (Table 28). Afforestation had an early effect, with very large reductions as early as the third year of the rotation: 6%/10% planted or 25 mm/10% (Figure 27). The very high yielding catchment was dry after eight years, complete desiccation probably having been accelerated by the drought of the early 1990's (Table 29). The catchment remained dry through four relatively dry hydrological years, 1991 to 1994. In August 1995 the riparian zone in the still dry catchment was cleared, and has been kept clear of coppice and weed growth subsequently. Following a particularly wet summer season over 1995/96, flow returned in the afforested catchment. Based on the pre-planting calibration the streamflow has continued to strengthen in the subsequent years, including the drier 1997 hydrological year (Figure 27, Table 29).

The riparian intervention complicated the experiment, and makes it difficult to identify the specific cause of the return of streamflow. It seems likely that both the clearing and the high rainfalls contributed to the restoration of streamflow. The absolute reductions in flow have more than halved since the catchment first dried up and immediately after the riparian treatment, from 45 mm/10% planted to less than 10 mm/10% in 1997 and 1998 (Figure 27). This makes it highly probable that the renewed streamflow is a reflection of general wetting of the catchment reflecting reduced water use by the maturing eucalypts.

Table 28 Details of the **calibration models** used in the analysis of weekly streamflow in **Catchment D, Westfalia.**

Dependent Variable	Model	Intercept (β_0)	Regression Coefficients (β_1)	Adjusted R^2	Error d.f*
Westfalia D Total flow 1	$\ln T = \beta_0 + \beta_1 . \ln C$	0.5646	0.7993	0.96	285
Westfalia D Total flow 2	$T = \beta_0 + \beta_1 . C^{½} + \beta_2 . C$	-3.945	4.1731	0.95	284

T = streamflow (mm) from treated catchment, Westfalia D
C = streamflow (mm) from control catchment, Westfalia B
* d.f. = degrees of freedom

There is not a particularly strong seasonal pattern to streamflows at Westfalia: dry season flows can be particularly strong, on average above 5 mm per month in the driest month (Figure 28). Consequently, all months are impacted strongly by afforestation though drier months are affected more than the wet months.

Table 29 Reductions in **total flows** at **Catchment D, Westfalia**, 83% afforested with *Eucalyptus grandis.* The reduction is calculated as the difference between the expected flow (based on the calibration relationship) and the observed flow. The five-year mean effect is shown in bold : CI is approximate confidence interval on each side of the mean.

Tree age (yrs)	Hydrological years	Annual Rainfall (mm)	Total flow reduction (mm)	95% CI (mm)	Total flow reduction (%)
0	1982	830	17.2	24.7	13.6
1	1983	1095	6.5	24.6	4.8
2	1984	1554	98.7	22.6	23.8
3	1985	1182	261.1	22.5	61.6
4	1986	1406	351.5	22.2	66.5
5	1987	1940	502.4	23.0	53.1
			206.2		**48.1**
6	1988	1130	344.9	22.3	72.1
7	1989	1477	406.2	22.2	77.1
8	1990	1201	380.6	22.5	87.3
9	1991	419	115.6	24.8	100.0
10	1992	737	129.7	24.7	100.0
			275.4		**81.6**
11	1993	1054	205.9	23.9	100.0
12	1994	1035	211.4	23.9	100.0
13	1995	954	448.4	22.5	52.2
14	1996	1861	349.5	24.2	31.8
15	1997	1189	84.2	22.5	19.0
			259.9		**46.1**

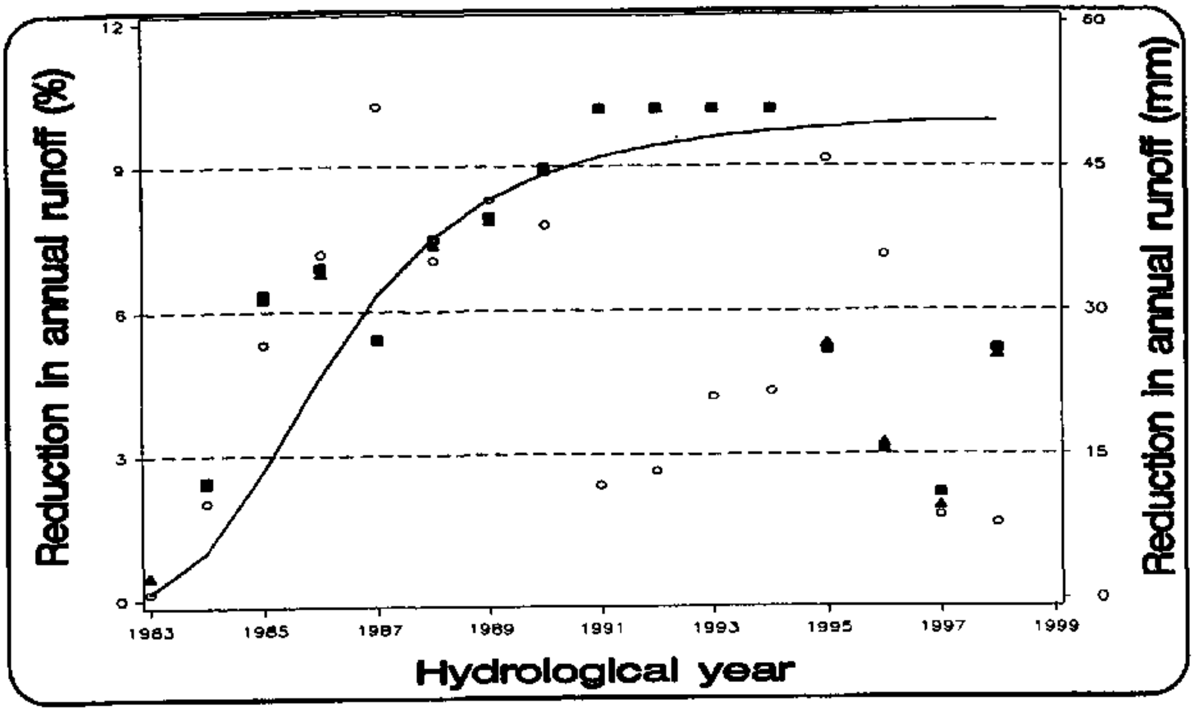


Figure 27 The relative reductions in **total flow** estimated by two different calibration models (▲ ■) and absolute reductions (open circles) in **Catchment D Westfalia** following 83% planting to eucalypts in 1991, plotted against hydrological year. The reductions are standardised to a 10% level of planting. The solid line represents the generalized total flow reductions predicted by the empirical curves of Scott and Smith (1997).

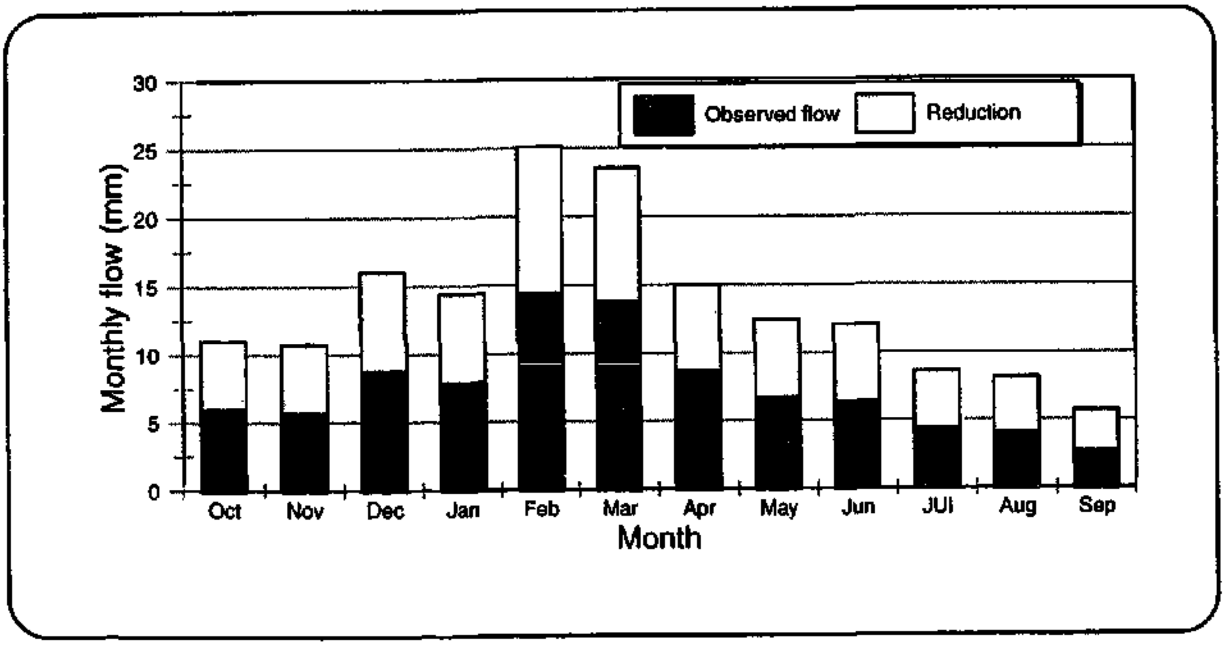


Figure 28 The mean monthly observed flows and estimated reductions as a result of afforestation in **Catchment D, Westfalia** over the period 1988 to 1991 once the trees were mature.

4.16 WESTFALIA A: CLEARFELLING EUCALYPT PLANTATION (80% *EUCALYPTUS GRANDIS*, 1991)

This catchment is small and poorly defined in terms of topography. Calibration with Catchment B is good (Table 30) over a fairly long pre-treatment period. In 1991, around the middle of the hydrological year (towards the end of the rain season), the *Eucalyptus grandis* plantation occupying 80% of the catchment was clearfelled at the normal rotation age for eucalypt sawlogs of 24 years. The clearfelled area was re-planted in the same year. Off a low base and during a drought period streamflow showed large relative increases, roughly 40%/10% cleared, but these were very small in absolute terms (4.5 mm/10% cleared) and were completely negated within four years (Figure 29, Table 31). The effect of clearfelling might have been practically insignificant because of a combination of the lower water use of mature eucalypts and the rapid re-vegetation of the catchment after clearfelling.

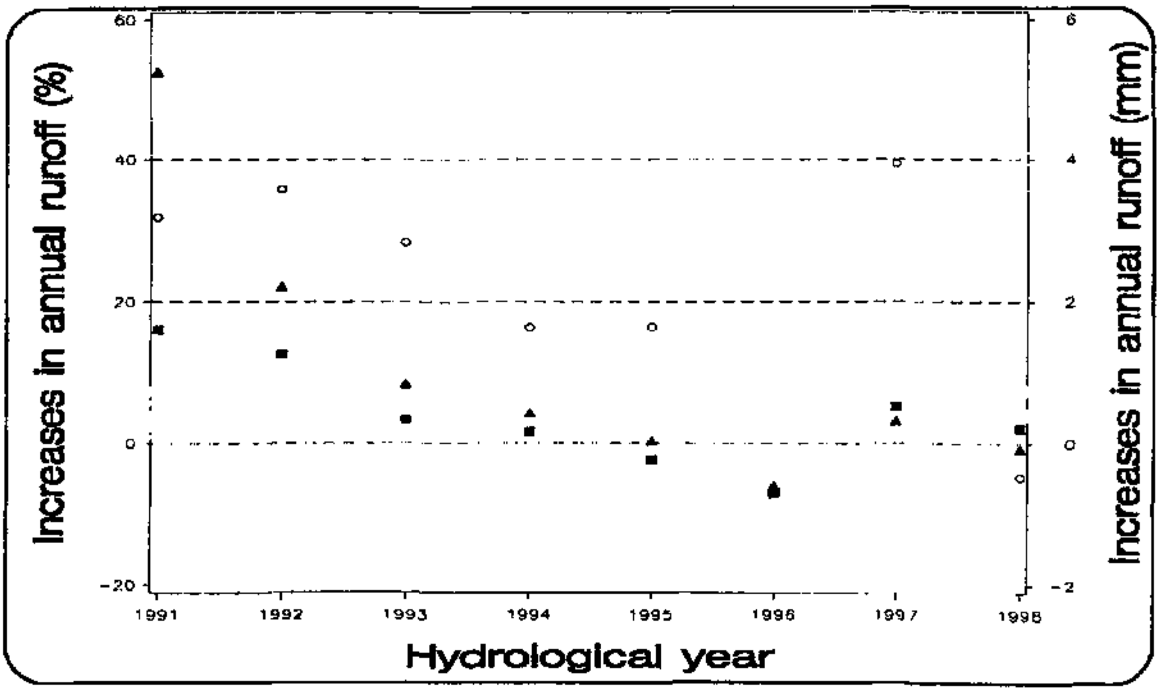


Figure 29 The relative increases in **total flow** estimated by two different calibration models (▲ ■) and absolute increases (open circles) in **Catchment A, Westfalia** following 80% clearfelling in 1991, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

Table 30 Details of the **calibration models** used in the analysis of weekly streamflow for **Catchment A, Westfalia**.

Dependent Variable	Model	Intercept (β_0)	Regression Coefficients (β_1)	Adjusted R^2	Error d.f*
Westfalia A Total flow 1	$ln\,T = \beta_0 + \beta_1.C^{½}$ $+ \beta_2.AW$	-0.2519	0.3743 0.00096	0.94	306
Westfalia A Total flow 2	$ln\,T = \beta_0 + \beta_1.C^{½}$ $+ \beta_2.C$	-0.5668	0.6565 -0.0164	0.93	306

T = streamflow (mm) from treated catchment, Westfalia A
C = streamflow (mm) from control catchment, Westfalia B
AW = antecedent wetness index, where decay factor is 0.92
* d.f. = degrees of freedom

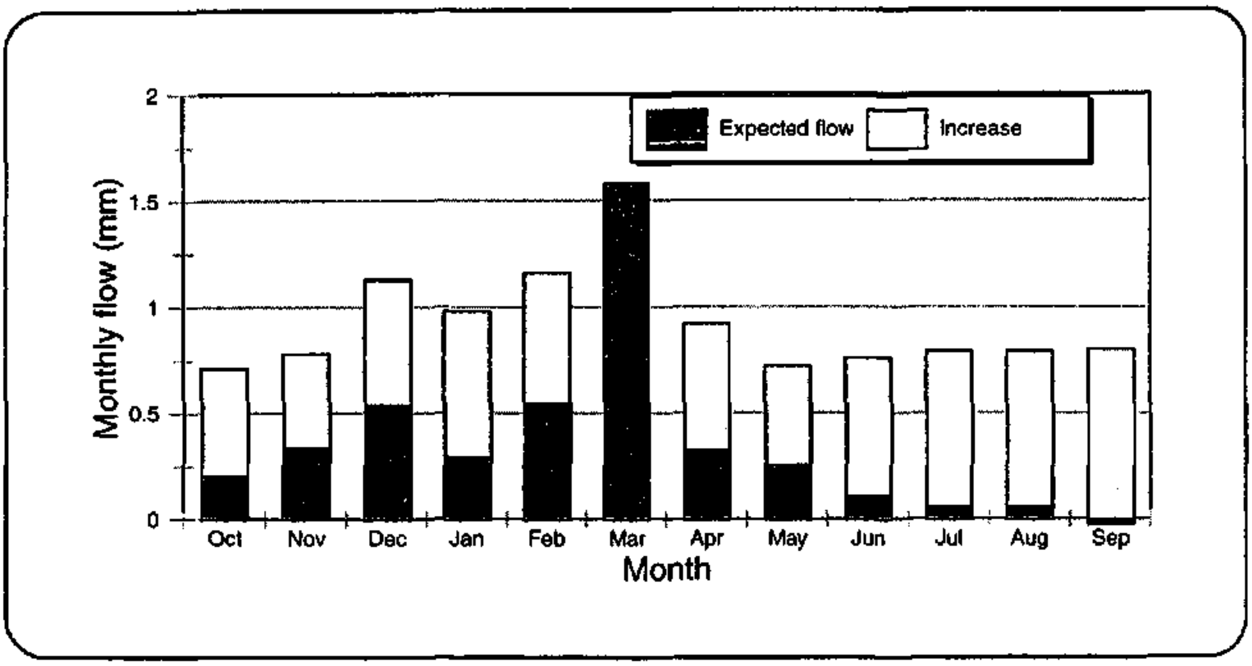


Figure 30 The mean monthly expected and estimated flow increases as a result of clearfelling in **Catchment A, Westfalia** for the first 3 years after felling (1991 - 1993).

Table 31 Increases in **total flows** at **Catchment A, Westfalia**, following clearfelling of *Eucalyptus grandis* over 80% of the area.

Tree age (yrs)	Hydrological year	Annual Rainfall (mm)	Total flow increase (mm)	95% CI (mm)	Total flow increase (%)
0	1991	419	25.5	21.4	421.0
1	1992	737	28.6	21.3	177.0
2	1993	1054	22.7	21.1	66.8
3	1994	1035	13.1	20.7	34.1
			22.5		**95.1**
4	1995	954	13.2	19.4	2.7
5	1996	1861	-326.8	12.2	-47.8
6	1997	1189	31.5	9.3	25.3
7	1998	854	-3.8	18.8	-6.8
			-71.5		**-21.2**

4.17 WITKLIP 6: CLEARFELLING OF PINE PLANTATION AND SOME EUCALYPTS (65% FELLING, 1978-'84)

The clearfelling was not planned as an experimental treatment, but a large area of plantation within this catchment was cleared over a five year period, though more than half the felling was done during 1979 and 1980, and replanting was not done promptly. The trees were old, the pines having been grown for sawlogs while the minor portion of eucalypts had been planted as a fire break. Witklip 6 has Catchment 5 nested within it, which provides an excellent correlation, but unfortunately there was clearfelling in Witklip 5 from 1982 onwards, which negates its value as a control. Instead, the planted but otherwise stable Catchment 3 was used as the long-term control (Table 32).

Table 32 Details of the **calibration models** used in the analysis of weekly streamflow in **Catchment 6, Witklip**. No low flow models were possible.

Dependent Variable	**Model**	**Intercept (β_0)**	**Regression Coefficients (β_1, β_2)**	**Adjusted R^2**	**Error d.f***
Witklip 6	$T = \beta_0 + \beta_1 Q5 + \beta_2 . AW2$	-0.8468	1.0475 0.0141	0.99	190
Witklip 6	$\ln T = \beta_0 + \beta_1 . \ln Q3 + \beta_2 . Q3^{1/4} + \beta_3 . AW$	-1.2857	0.0070 -0.395570	0.87	160

T = streamflow (mm) from treated catchment, Witklip 6
Q5, Q3 = streamflow (mm) from control catchments, Witklip 5 and Witklip 3, respectively.
AW, AW2 = antecedent wetness by two decay factors (0.85, 0.2)
* d.f. = degrees of freedom

Increases in total flow were measured in Witklip 6 from the first year of harvesting, and these became steadily larger with the area being felled (Figure 31). The highest percentage flow increase was 11%/10% in 1982 though absolute increases of between 50 to 60 mm/10% of catchment cleared were recorded later in the wet hydrological years of 1984 and 1985.

Streamflow appeared to have returned to pre-cutting levels by 1988, presumably as the plantations became dominant again (Table 33).

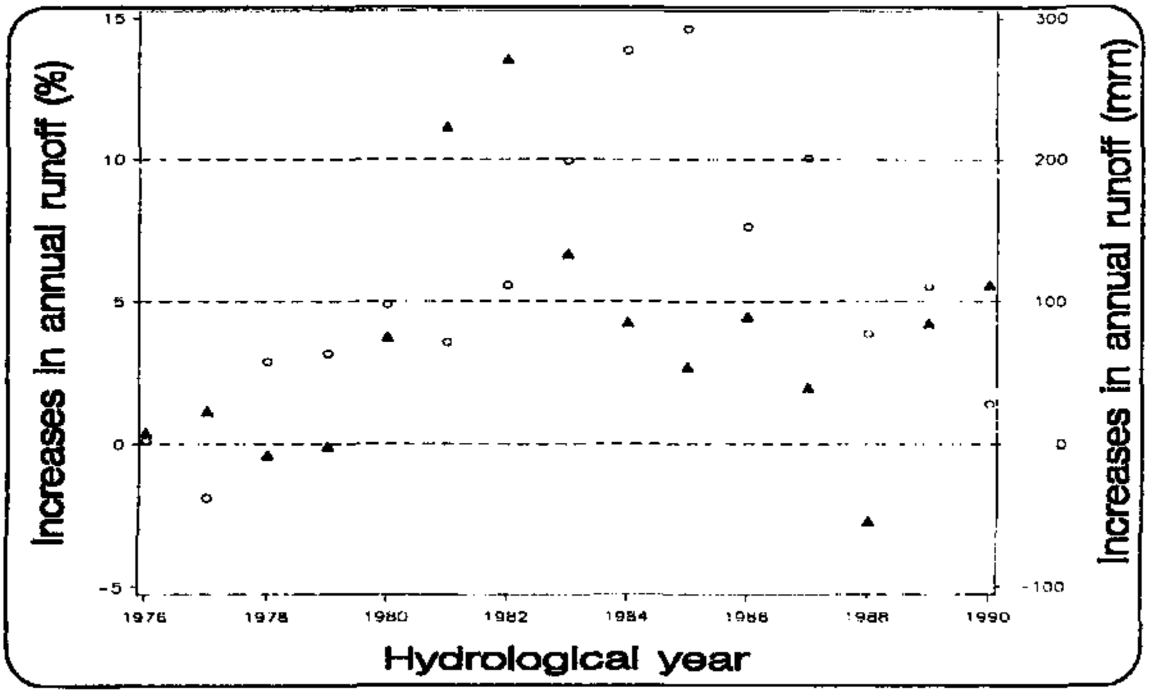


Figure 31 The relative increases in **total flow (▲)** and absolute increases (open circles) in **Catchment 6 Witklip** following clearfelling between 1978 and 1984, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

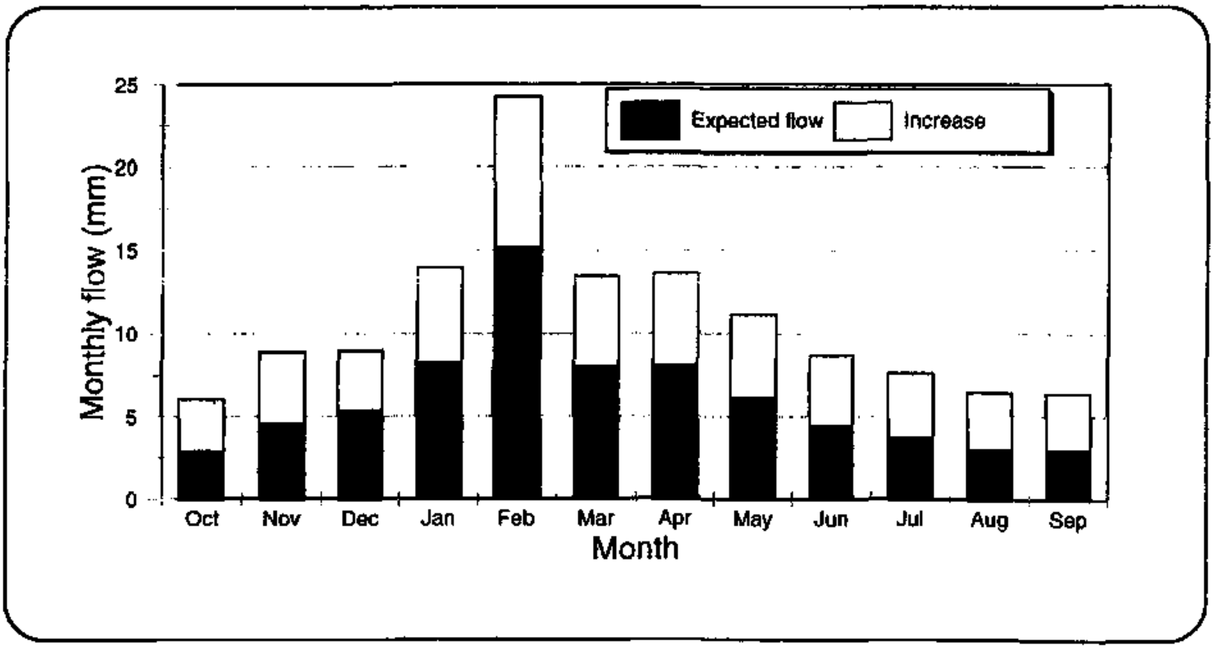


Figure 32 The mean monthly expected flow and estimated flow increases as a result of clearfelling in **Catchment 6 Witklip** for over the period of clearfelling 65% of the catchment area of plantation between 1978 to 1984.

Table 33 The observed flow and estimated total flow increases in **Catchment 6, Witklip** following clearfelling between 1978 and 1984. Mean increases are shown in bold: CI indicates the approximate confidence limits on the increases.

Tree age (yrs)	**Hydrological year**	**Annual rainfall (mm)**	**Total flow increase (mm)**	**95% CI (mm)**	**Total flow increase (%)**
0	1978	912	-3.8	9.7	-2.5
1	1979	1264	-1.5	10.1	-0.5
2	1980	1104	62.2	10.0	24.4
3	1981	851	75.9	9.7	72.5
4	1982	682	73.1	9.6	88.2
			41.2		**23.1**
5	1983	1196	98.3	9.9	43.4
6	1984	1072	108.5	10.4	27.6
7	1985	1206	72.4	10.5	17.5
8	1986	807	46.8	9.7	29.0
			81.5		**27.3**
9	1987	1098	44.2	10.2	12.9
10	1988	1091	-64.4	10.3	-17.6
11	1989	1025	79.4	10.1	27.5
12	1990		15.4	9.6	36.3
			18.7		**7.2**

4.18 WITKLIP 5: CLEARFELLING OF PINE PLANTATION AND SOME EUCALYPTS (51% FELLING, 1978-82)

The calibration with Witklip 3 is only reasonable, though the low flow models are better (Table 35). As in Witklip 6 clearfelling took place on a piecemeal basis, between 1982 and 1984. Significant flow increases were recorded in 1983, peaked in the wet years of 1984 and 1985 at low levels of 7 to 9 mm/10% cleared (Figures 33 and 34; Table 34). Flows are fairly sustained throughout the year with peak summer flows only being within three times the lowest flow (Figure 35) and the effect of forestry is clearly greater in relative terms during the dry season.

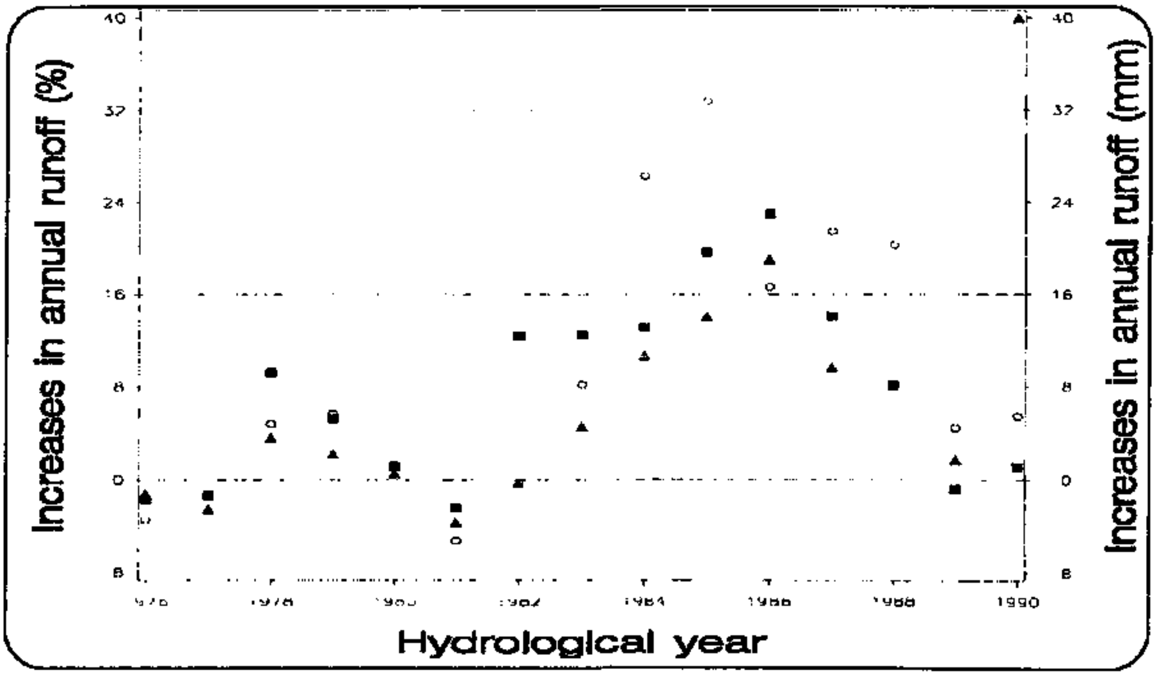


Figure 33 The relative increases in **total flow** estimated by two calibration models (▲ ■) and absolute increases (open circles) in **Catchment 5, Witklip** following clearfelling between 1982 and 1984, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

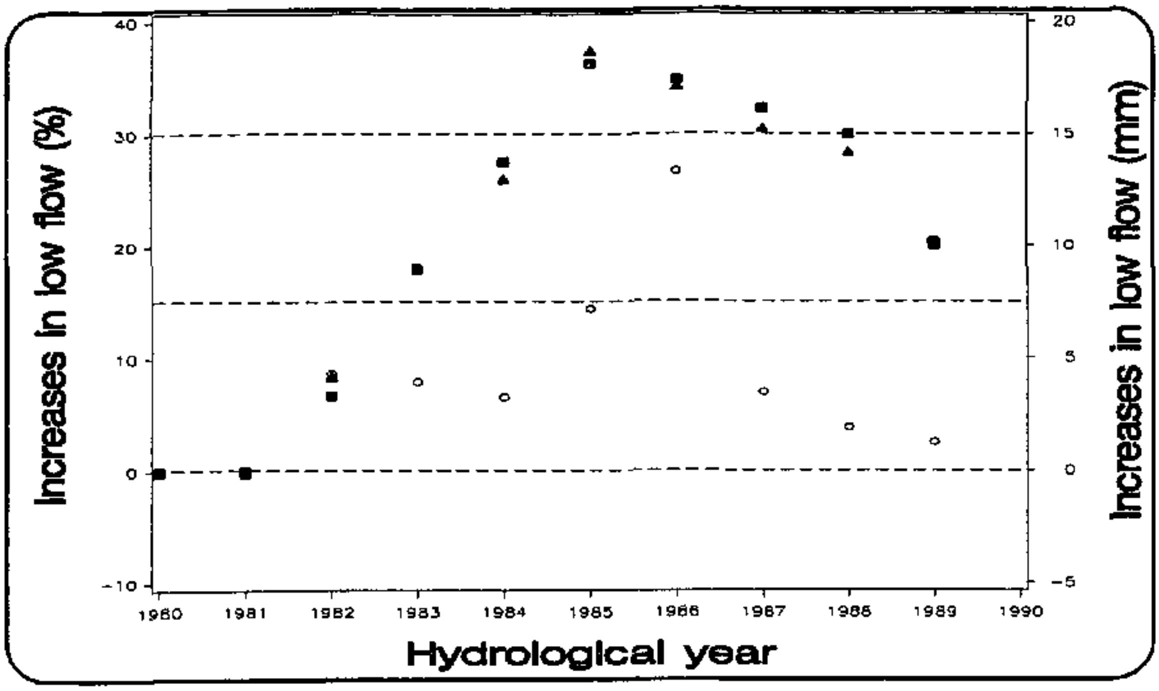


Figure 34 The relative increases in **low flow** estimated by two calibration models (▲ ■) and absolute increases (open circles) in **Catchment 5, Witklip** following clearfelling between 1982 and 1984, plotted against the hydrological year. The increases are standardised to a 10% level of clearing.

Table 34 The observed flow and estimated increases in flow in **Catchment 5, Witklip** following clearfelling over 51% of the catchment area between 1982 and 1984.

Tree age (yrs)	Hydrological year	Annual Rainfall (mm)	Total flow increase (mm)	95% CI (mm)	Total flow increase (%)	Low flow increase (mm)	95% CI (mm)	Low flow increase (%)
0	1982	882	-1.3	15.6	-1.4	21.9	4.0	42.7
1	1983	1196	41.7	13.9	23.1	20.0	4.7	91.2
2	1984	1072	134.0	14.2	54.1	16.6	4.2	132.6
3	1985	1206	167.0	4.8	71.8	36.6	5.8	190.7
			85.3		**45.2**	**23.8**		**90.6**
4	1986	807	84.8	14.5	96.8	68.0	4.8	174.7
5	1987	1098	109.4	13.7	49.1	17.6	5.3	155.5
6	1988	1091	103.5	13.5	41.0	9.7	5.3	144.8
7	1989	1025	22.7	20.4	8.7	6.4	3.0	102.2
8	1990		27.8	4.0	203.8	**25.4**		160.9
			69.6		**41.5**			

Table 35 Details of the **calibration models** used in the analysis of weekly streamflow in **Witklip 5.**

Dependent Variable	Model	Intercept (β_0)	Regression coefficients (β_1, β_2)	Adjusted R^2	Error d.f*
Witklip 5: Total flow 1	$T = \beta_0 + \beta_1 C^{1/4} + \beta_2.C^{1/2}$ $AW + \beta_3.AW2$	-0.9717	0.2096 0.0043 0.0177	0.76	369
Witklip 5 Total flow 2	$\ln T = \beta_0 + \beta_1.\ln C^{1/2} +$ $\beta_2.C^{1/2}$	-0.9661	1.2281 -0.0113	0.80	370
Witklip 5: Low flow 1	$T = \beta_0 + \beta_1$ $\beta_1((C^{1/2}\ AW)/_{100}) + \beta_2.AW2$	-1.6575	0.1289 0.0136	0.89	53
Witklip 5: Low flow 2	$\ln T = \beta_0 + \beta_1.$ $\beta_1((C^{1/2}\ AW)/_{100}) + \beta_2.AW2$	-0.4998	0.0600 0.0058	0.91	53

T = streamflow (mm) from treated catchment, Witklip 5
C = streamflow (mm) from control catchment, Witklip 3
AW, AW2 = antecedent wetness by two decay factors (0.9, 0.2)
* d.f. = degrees of freedom

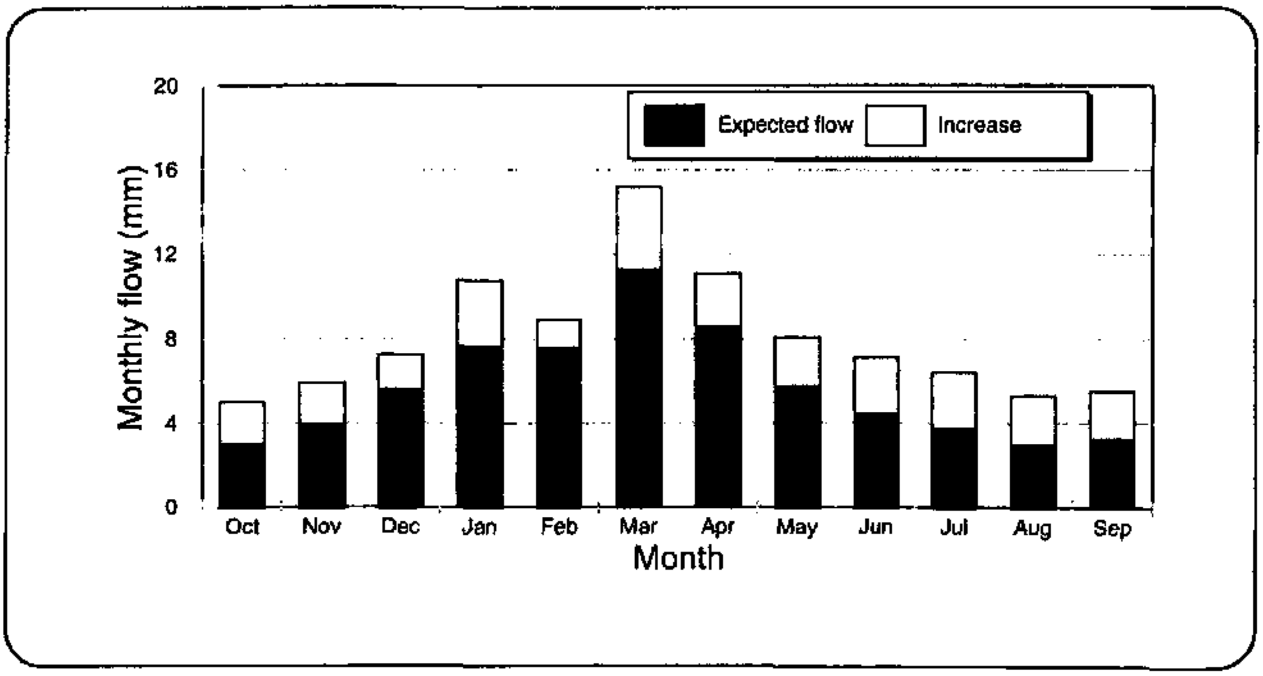


Figure 35 The mean monthly expected flow and estimated increase as a result of clearfelling in **Catchment 5, Witklip** over the first 4 years after felling (1982 to 1985).

4.19 NTABAMHLOPE CATCHMENTS V7H004 & 8: AFFORESTATION, *EUCALYPTUS MACARTHURI*, 1990.

At Ntabamhlope the calibration models are limited by the short period of pre-treatment data that is available and the disparity between the treated and control catchments (Table 36). However, though the regression models are not especially tight, they are satisfactory particularly when one considers that there is a small earth wall dam in the control catchment, V7H003.

The absolute effects of planting were not quantified because of the poor overall record of streamflows that are available, but it is very clear that the effect of forestry has been to dry the catchments up within the first five years of planting (Figures 36 and 37). The early part of the record after planting is incomplete in Catchment 8 but, by the first and third hydrological years after planting the flow reductions in Catchments 4 and 8, respectively, were significant. In the 1994 hydrological year neither planted catchment had any flow, and in the fifth year, a particularly wet year, flow in 4 and 8 was only 0.3% and 44% of expected, respectively. This result is particularly significant given the importance of these catchments as representative of afforestation with hardier eucalypts in lower rainfall regions.

Table 36 Details of the **calibration models** used in the analysis of monthly streamflow in **Ntabamhlope** catchments 4 & 8 (V7H004 & 8) with catchment 3 (V7H003) as the control.

Dependent Variable	Model	Intercept (β_0)	Regression Coefficients (β_1)	Adjusted R^2	Error d.f*
Monthly flow 4 (m^3)	$T = \beta_0 + \beta_1 C$	533.9041	2.6662	0.71	20
Monthly flow 8 (m^3)	$T = \beta_0 + \beta_1 C$	4174.4916	1.9681	0.85	21

T = streamflow (mm) from treated catchments (V7H004 or V7H008)
C = streamflow (mm) from control catchment (V7H003)
* d.f. = degrees of freedom

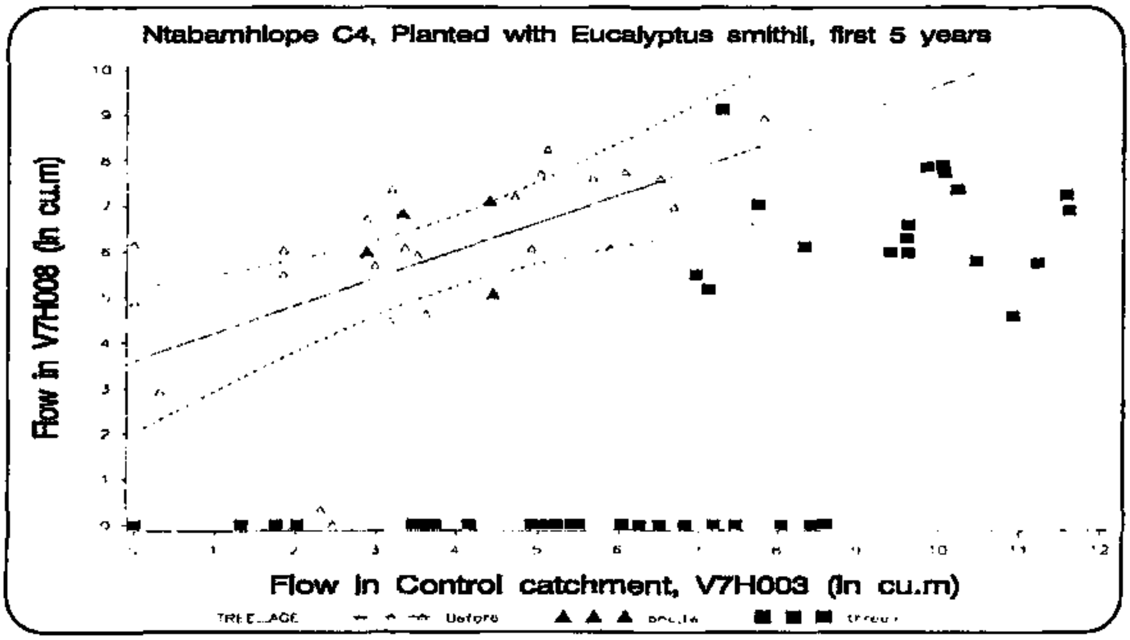


Figure 36 Plot of flows in **Catchment 4 Ntabamhlope** (V7H004) against corresponding monthly flows in control **Catchment 3** (V7H003). Solid symbols indicate years after planting of eucalypts. The regression model is fitted to pre-treatment points only and the dashed line indicates the 95% confidence limits.

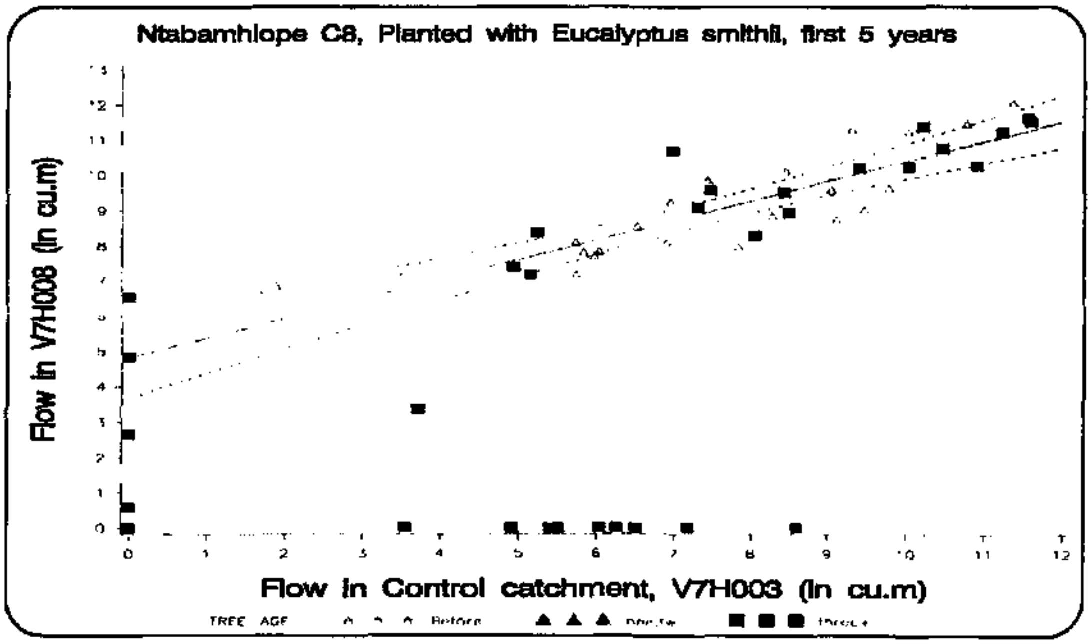


Figure 37 Plot of flows in **Catchment 8 Ntabamhlope** (V7H008) against corresponding monthly flows in control **Catchment 3** (V7H003). Solid symbols indicate years after planting of eucalypts. The regression model is fitted to pre-treatment points only and the dashed line indicates the 95% confidence limits.

5. DISCUSSION

5.1 UNDERSTANDING THE DRIVERS OF AFFORESTATION EFFECTS

The most important determinants of the flow reductions following afforestation are the level of planting (proportion of a catchment), the tree type (pine or eucalypt) and water availability. The degree of planting can be scaled out of the picture fairly successfully, and the effects of pines and eucalypts are viewed separately. This leaves water availability. Wet catchments, those with the highest water availability, have the highest flow reductions. This is probably because water demand is generally greater than supply in South African conditions (situations where supply is unlimited are rare in this country). Good examples of this point are the wet Cathedral Peak II and Tierkloof where 5-year mean estimated peak reductions were 67 and 54 mm/10%, respectively. From this it also follows that wet years are those in which the highest reductions are measured. This point is illustrated by Mokobulaan A & B that were both dry for the latter half of the rotations but because of differences in rainfall the estimated 5-year mean maxima were sharply different at 41 and 17 mm/10% respectively.

Conversely, low water availability can lead to bigger relative reductions, earlier in the rotation, e.g. Mokobulaan B under pine reached a 100% reduction in 12 years under a dry cycle and the dry Ntabamhlope catchments, planted to a hardy eucalypt, reached 100% reductions in the fourth year of the rotation.

5.2 PERFORMANCE OF THE EMPIRICAL FLOW REDUCTION MODELS

The empirical curves developed by Scott & Smith (1997) are currently used to estimate the probable impact of afforestation schemes. The additional experiments analysed in this study offer an opportunity to verify these models. The estimated flow reductions in each experiment are plotted against time after planting. Each of these also plots the flow reduction that would be predicted by the generalized flow reduction models of Scott & Smith (1997). Several points can be made regarding the adequacy of the generalized models.

In broad terms the results show that the curves often underestimate the early effects of afforestation, especially for the longer rotation pine experiments in Jonkershoek and the eucalypt crops at the drier Ntabamhlope site. Furthermore, the curves are asymptotic, remaining at a maximum for the latter part of a rotation. This shape seems to be realistic for short rotation crops and in drier areas, where water demand will usually exceed supply for the duration of the rotation. For the longer rotation crops (probably over 15 and 20 years for eucalypts and pines respectively) on more humid sites the flow reduction curves will need to be modified to replicate the shape of a growth curve, to predict a gradually declining influence of the trees on streamflow.

There is much variation about the curves and the fit is seldom tight, though the fit is notably better for some catchments as opposed to others. Variation has numerous sources and it is not possible to fully explain these without detailed analysis of each case. The probable sources include variations in rainfall from year to year that results in differences in water storage in the two modelled catchments, differences between the catchments in their responses to individual storms or storm types.

The most obvious and predominant source of variation in afforestation effects is the degree of planting or clearfelling. Treatment effects are generally less clearly defined and there is greater unexplained variation where the proportion of a catchment that has been treated is smaller. See for example Tierkloof, where only 36% of the highly responsive catchment has been planted (Figures 10 and 11). It is possible to standardise the results for the level of treatment, but this does not remove the variation.

It is also apparent that the low flow models are less efficient in explaining variations than are total flow models, with the result that there is generally greater variation about the low flow models. See for example the difference between Figures 10 and 11.

The models generally mimic the form of flow reductions correctly, but the timing of the onset of reductions, degree and timing of peak reductions is quite variable. The diminishing effect of forestry with time is clear in the new results but the degree of this diminution and its timing appears to be highly variable, and will be difficult to model with accuracy at this time..

The best fit of the general curves is in the catchments to which the original models were fitted. Obviously this is as expected though the computational units (weekly volumes) and regression models developed in this exercise were different from those developed in the original analysis. These catchments are Cathedral Peak III, Lambrechtsbos-B, Mokobulaan A and B and Westfalia-D (Figures 22, 23, 13, 25, 26 and 27). In each the fit of the models is understandably good.

Other cases where the models performed very well, and where one could say that the models had been successfully verified, are Cathedral Peak II (Figures 19 and 20) and Biesievlei (Figures 6 and 7). With the exception of Biesievlei (Figures 6 and 7) the major failing of the Scott and Smith curves is that the asymptote is higher than observed in most experiments. Also, a general pattern that the models do not reflect is the diminished streamflow reductions late in the rotation.

Overall, it is also clear from the plots of effects over time that the general empirical models provide only an average and long-term estimate of the reductions caused by afforestation. There is a substantial variation in the key components: time to initiation of flow reductions after planting, size of reductions in individual years, and size of effects in the later years of long rotations. Deviations from prediction in any individual year can be quite large, though over a series of years cumulative deviations are much smaller. Confidence limits about predictions though are generally quite large.

5.3 UNDERSTANDING THE DIMINISHED EFFECTS IN LONG ROTATIONS

This study has established, for South African plantation forestry conditions, that flow reductions are not sustained at an asymptote *indefinitely*. As plantations mature so they have a diminished effect on streamflows relative to earlier in the rotation. The timing of these decreases is not adequately understood at this stage. In this respect the catchment results are beginning to produce a similar pattern, though with different time scales, to the measured transpiration cycle of young *Eucalyptus grandis* stands in Mpumalanga (Olbrich, 1994) and the response in streamflow to fire in, and regrowth of, mountain ash (*Eucalyptus regnans*) forest in Victoria, Australia (Langford, 1976; Kuczera, 1987) and over-mature fynbos (Scott, 1994). Olbrich showed that young *E. grandis* stands had peak transpiration rates around 3 years of age, and that stand-level transpiration declined after this peak in association with decreased leaf area index and water use per unit of leaf area. Wildfire in the mountain ash forests near Melbourne led to very brief increases in streamflow (for two to three years), followed by large decreases in flow while the young ash regrowth developed and matured. Beyond an age of roughly 30 years, streamflow from these forests increased again (Langford 1976, Kuczera, 1987), and the management of these important water catchment areas consequently strives to maintain mature forest as a means of sustaining high yields of good quality water. More recent work on these *Eucalyptus regnans* forests has related increasing streamflow in maturing forest (over 30 years) to a declining sapwood area and interception loss (Haydon *et al.*, 1996). In a similar way, clearfelling of mature indigenous evergreen forest on the Westfalia estate did not lead to substantial or sustained streamflow increases, but rather to a flow reduction once vegetation had recovered a canopy on the site (within a year) even though the biomass was much smaller (Scott and Lesch, 1996).

The results prompt the hypothesis that the catchment is a large reservoir formed of deeply weathered soil and therefore acts as a buffer for short-term changes in components of the hydrological cycle. Large increases in evaporative losses, such as occur after the establishment of fast growing plantations into grassland, draw on the reservoir of the catchment as well as rainfall in the current year. The effects of afforestation on streamflow therefore become lagged. In other words, changes in storage of water within the catchment vary from year to year and are important in smoothing the response in streamflow to change in vegetation. Once evaporative losses decline such as occurs with maturing trees or after clearfelling or fire, the catchment reservoir must first be recharged before full streamflow recovery will be recorded. In some cases, such as after clearing of mature pine in Jonkershoek and Witklip this recovery was very rapid. The wet Jonkershoek catchments appear to be recharged on an almost annual basis. However, the Mokobulaan and Westfalia catchments required longer for full restoration of water storage to occur, and thus the effects of one rotation of timber can be stretched into the next. Eucalypts may root more deeply and thereby create a greater storage deficit as appears to be the case at Mokobulaan. Above average rainfall will fully replenish stores in shorter time (one or two years). These points hold major implications for research priorities.

6. CONCLUSIONS

There is a large variability in the results of these experiments; both natural variability caused by site and species differences and climatic variation and the sequence of climatic events, and statistical variability related to the method of analysis. The latter involves different responses in two similar catchments to specific climatic events or the inability of the statistical models to replicate a seasonally specific response. Streamflow response is an integral of all hydrological processes, and streamflow generation is a complex process and probably unique for each catchment. Hence it is a source of variation that is not, and is likely to remain, inadequately explained in paired catchment comparisons.

Consequently:-

1. There is a need for long periods of data in order that one can develop a full picture of land use effects through the natural variations that would otherwise obscure the picture.
2. For the above reasons, replication is vital. A single catchment cannot provide proper insight, nor can a single climatic sequence provide an understanding of how a response will vary under different rainfall cycles. Replication therefore involves different species, sites and times of planting.

The initial onset of flow reductions has been underestimated for the bulk of pine plantations. Whereas a long lag before flow reductions become significant has become the general expectation, many of the additional experiments analysed here show that flow reductions can be substantial from an earlier stage in the rotation. As most forestry in South Africa is now in second or higher rotations and there is much less competing vegetation at the time of replanting, long lags prior to there being significant effects on streamflow are probably most unlikely.

It is clear from this review and updated analysis that flow reductions are not sustained at an asymptote indefinitely. Over longer rotations, there is a negative relationship between plantation age and streamflow reductions. This means that during the later stages of a long sawlog rotation some degree of replenishment of soil water stores occurs, to counter-balance net losses from storage in the early part of the rotation. The implication of this finding is that the hydrological effects of long rotation crops has probably been over-estimated in the past, and the hydrological effects of short rotation crops, such as eucalypt pulp and mining timber, has been under-estimated (because of a lag between evaporation and streamflow response).

As plantations mature so they have a lower hydrological impact than earlier in the rotation. The timing of these decreases is uncertain at this stage. In this respect the catchment results are beginning to produce a similar pattern, though with different time scales, to the measured transpiration cycle of young *Eucalyptus grandis* stands in Mpumalanga, the response in streamflow to fire in, and regrowth of, mountain ash (*Eucalyptus regnans*) forest in Australia and over-mature fynbos, and indigenous scrub forest in South Africa (as discussed in Section 5.3 above).

The key to predicting the dimension of this lag effect would appear to be the storage capacity of an individual catchment, the rooting behaviour of the crop in that catchment and the rainfall surplus in a particular sequence of years. Most of the research catchments, and probably most of the humid forestry areas, have hydrologically deep soil mantles - deeply weathered and freely draining with the result that subsurface water stores are very substantial. Eucalypts may root more deeply and create a greater storage deficit as appears to be the case at Mokobulaan. Above average rainfall will fully replenish stores in a shorter time (one or two years).

These considerations show that it is important to understand that water is routed through the soil mantle, and not over it in these kinds of catchments and under a forest cover. Models that ignore this fact are not likely to be able to replicate the observed results, least of all on a seasonal basis. Models need to be able to provide for deep and substantial water storage capacity and a long time frame in the cycling of water through the system. These points hold major implications for research priorities.

Despite the observed variation in afforestation effects, the generally accepted pattern and magnitude of streamflow decreases over the normal rotation length of productive plantations has been confirmed by this study. Pine and eucalypt plantations cause large reductions in streamflow; reductions peak between five and ten years after planting of eucalypts, and between 10 and 20 years after planting with pines, and the size of the reductions is limited primarily by water availability. Aspects which can be viewed differently following this review are as follows.

- The initial onset of flow reductions has been underestimated for the bulk of pine plantations. Whereas a long lag before flow reductions has become the general expectation, many of the experiments here show that flow reductions can be important from an earlier stage in the rotation. As most forestry in South Africa is now in second or higher rotations and there is much less competing vegetation at the time of replanting, long lags prior to there being significant effects on streamflow are probably most unlikely.
- The peak flow reductions are probably determined by an absolute availability rather than by some relative maximum (as suggested by the empirical curves of Scott & Smith 1997). Where maximum availability coincides with high atmospheric demand it seems probable that the peak reductions will be greater. Such maxima could be between 30 - 40 mm/10% planted to pine in the winter rainfall area and between 40 - 50 mm/10% planted to pine or eucalypts in the summer rainfall areas. At sites where availability is less than the expected maximum reduction, the streams can be expected to dry up, as was the case in Westfalia, Mokobulaan and Ntabamhlope.
- Over longer rotations, there is a negative relationship between plantation age and streamflow reductions. This means that during the later stages of a long sawlog rotation some degree of replenishment of soil water stores occurs, to counter-balance net losses from storage in the early part of the rotation. The implication of this finding is that the hydrological effects of long rotation crops has probably been over-estimated in the past, and the hydrological effects of short rotation crops, such as eucalypt pulp and mining timber, has been under-estimated (because of a lag between evaporation and streamflow response).

7. RECOMMENDATIONS FOR FUTURE WORK

7.1 WORK PLANNED BUT NOT ACCOMPLISHED

Some aspects of the originally envisioned work could not be completed within the time and budget of this project. These were essentially the following three aspects.

- It was planned that the secondary data would be used to explore the effects of forestry in relation to wet and dry years or cycles, in other words to explore the relationship between flow reductions and rainfall year (or general catchment wetness), i.e. the effects of forestry in wet and dry years and through wet and dry cycles. There is considerable speculation over this relationship which is of particular relevance for the estimation of the supply of water to run-of-river water users and calculations of the reserve. It is also important to establish the nature of this relationship in order to establish a proper baseline against which the realism of modelling efforts can be tested.

- Secondly, it was hoped that from the full hydrological records, the effects of forestry on stormflows could be addressed.

- Finally, the current project has not investigated the environmental variables that might add explanation to observed variation in forestry effects between different catchments and different years. Amongst the environmental drivers, for example, that might be tested for an influence on observed effects are rainfall, temperature, soil depth or tree rooting characteristics.

7.2 FURTHER ASPECTS ARISING DIRECTLY FROM THIS PROJECT

The current study has been far from exhaustive. The main product of the project has been to prepare and check this vast body of invaluable data making it available for analysis. Many secrets and information remain locked up in the data, both in terms of the hydrological effects of afforestation of fynbos, forest and grassland, but also in the pure understanding of headwater catchment hydrology. The "SAFRI" research catchments hydrological data can still be used to answer many hydrological questions, as the needs arise and finances and other resources become available.

The major part of the current project went into data preparation, and relatively little time was spent on analysis. However, the project has now produced a large series of secondary data sets, namely, the estimated flow reductions or increases over time following afforestation or clearfelling, respectively. Aspects that can be readily researched from this base include some of the projects mentioned above. As the secondary data (i.e. observed effects) are available, there are several additional aspects that may be studied at relatively little extra cost. These are listed in brief below.

- Clarify the effects of forestry by further analysis, specifically characterising the onset and extent of the diminished effects late in the rotation, and determine the influence within each catchment of annual rainfall characteristics.
- Investigation of patterns in the flow duration curves through the forestry rotations.
- Refinement of the empirical flow reduction models to incorporate the increased understanding developed through the additional analyses accomplished by this project.
- Setting up generalised limits to the effects of forestry within various climatic conditions for different types of forestry, as a basis for checking the results of deterministic modelling efforts.
- Analyse afforestation effects within one catchment relative to annual rainfall or rainfall characteristics.
- Explore the variation in results between adjacent catchments.
- Attempt to identify the determinants of absolute maxima or asymptotes, e.g. at Cathedral Peak *vs* Jonkershoek *vs* Westfalia.

7.3 THE FUTURE OF THE EXPERIMENTAL CATCHMENTS

There is obviously still valuable information to be gained from the afforested research catchments. It is therefore recommended that research persist with consistent management of the plantations over extended periods. The specific objective is to obtain information from two important sources, firstly replication - same experiments, different species, location, conditions and/or set of environmental drivers; and, secondly, the length of the experiments which will add information on the timing and drivers of the declining influence on streamflow later in the rotation.

In future, process studies ought to be done within gauged catchments such that the context of process studies is known. The value of results from detailed process studies (for example, measurements of transpiration) are diminished because the broader hydrological context is missing. By this means, process studies would be greatly enhanced by being done where the total hydrological effects are understood and bounds can be placed on the range of values. In the same way, the value of the catchment experiments is diminished because of the paucity of process understanding that has been associated with the specific catchment.

7.4 FURTHER WORK ON UNDERSTANDING LAND COVER CHANGE EFFECTS AND MODELLING THESE

In order to properly model the hydrological effects of forestry, research is needed on the hydrological function of catchments: how water moves through a catchment, how streamflow is actually generated and the estimation of reservoir size and residence times of water.

Secondly, from the perspective of understanding the hydrological effects of different land uses, research needs to clarify both the size and temporal pattern of water use (total evaporative loss) under different land covers, and to investigate the effects of different crops and associated land management practices on hydrological processes. Specifically, one needs to understand how rainfall is partitioned between overland and subsurface routes to the stream.

Considering afforestation effects, more work is needed on important types and localities of forestry that are under-represented by the existing research network. Specifically, the hydrological characteristics of wattle (predominantly *Acacia mearnsii*) are very poorly understood, though this is an important crop type and the area under this crop may grow further. Wattle currently forms 10% of all formal plantings and a larger part of informal plantings (woodlots). Another component that is poorly understood are the effect of plantations, particularly cold tolerant eucalypts and wattle, that are grown on the highveld and other lower rainfall areas (MAP < 1000 mm).

The catchment experiment approach has proved to be extremely valuable, and it is important that future research also build on the firm foundation provided by this methodology. There is a temptation to dispense with the slow, inflexible and costly catchment experiments, but the real basis that this provides for other research work and modelling make catchments an invaluable element of future studies. This is particularly important in understanding the integrated effects of important agricultural practices and crops, for instance, sugar.

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APPENDIX 1

CATALOGUE OF DATA

Introduction: The data catalogue is a list of streamflow, precipitation and information files. All the files are in units of daily totals. These intervals were calculated from 00h00 to 24h00 for each day. Raingauge 12b has weekly totals. All the data files (streamflow and rainfall) have mm units although streamflow is also given as cubic meter volumes. The information (inquiry) files show where the gaps in the data occur.

Streamflow (q)

	Catchment		*File name*	*Reference list*		
Jonkershoek	Bosboukloof	-	bbk_q.day	Jonkershoek	=	Western Cape
	Biesievlei	-	bv_q.day	Cathedral Peak	=	Kwazulu - Natal
	Tierkloof	-	tk_q.day	Witklip	=	Mpumalanga
	Lambrechsbos A	-	lba_q.day	Mokobulaan	=	Mpumalanga
	Lambrechsbos B	-	lbb_q.day	Westfalia	=	Northern Province
	Langrivier	-	lr_q.day			
				q	=	Streamflow
Cathedral Peak	Catchment II	-	cp_ii_q.day	p	=	Precipitation
	Catchment III	-	cp_iii_q.day	day	=	Daily

	Catchment IV	-	cp_iv_q.day	wk	=	Weekly
				inq	=	Inquiry
Witklip	Witklip_5	}		qp	=	combined q & p
	Witklip_6	}	wi_56_qp.day			
Mokobulaan	Catchment A	}				
	Catchment B	}	m_abc_qp.day			
	Catchment C	}				
Westfalia	Catchment B	}				
	Catchment D	}	w_bd_qp.day			

Precipitation (p)

	Catchment		*File name*
Jonkershoek	Bosboukloof	-	11a_r.day
	Biesievlei	-	12b_r.wk
	Tierkloof	-	13a_r.day
	Lambrechsbos A }	-	15a_r.day
	Lambrechsbos B }		
Cathedral Peak	Catchment II	-	rg_2_cp.day
Westfalia	Catchment A	-	rg_3_wf.day
Witklip	Witklip_6	-	rg_6_wi.day

Meta Data Record Inquiry : Information on the data files and breaks in each record

	Catchment		*Streamflow (q)*	*Precipitation (p)*
Jonkershoek	Bosboukloof	-	bk3898.inq	11a.inq
	Biesievlei	-	bv3898.inq	
	Tierkloof	-	tk3898.inq	13a.inq
	Lambrechsbos A	-	lba4692.inq	15a.inq
	Lambrechsbos B	-	lbb4798.inq	
	Langrivier	-	lr4098.inq	
Cathedral Peak	Catchment II	-	cpii4893.inq	rg2cp.inq
	Catchment III	-	cpiii5291.inq	
	Catchment IV	-	cpiv4993.inq	
Witklip	Witklip_5	-	wi5_7591.inq	
	Witklip_6	-	wi6_7591.inq	rg6wi.inq
Mokobulaan	Catchment A	-	m_a_5782.inq	
	Catchment B	-	m_b_5782.inq	
	Catchment C	-	m_c_5797.inq	
Westfalia	Catchment B	-	w_b_7598.inq	rg3wf.inq
	Catchment D	-	w_d_7598.inq	

APPENDIX 2

CATCHMENT HISTORIES

JONKERSHOEK

Bosboukloof (200 ha)	
Date	**Treatment**
Aug. 1937	Raingauge 11A commenced gauging
1937/38	Onset of afforestation with *P. radiata* ; espacement 2.7x2.7m giving 1330 stems per hectare (s.p.h.), 20 m strips left either side of streams with natural vegetation; Compartments 11b (10.52ha) and 11d (4.45ha) with *P.radiata* (north-western side of catchment; roughly 20 % of these areas not within catchment area); 11e (0.16ha) and 11f (0.24ha) with *P. can.*
1 Jan. 1937	Streamflow gauging commenced
1938/39	Afforestation of compartments 12 (6.88ha), 13b (8.60ha), 13f (5.68ha), 13h (2.84ha), 23b (8.92ha), 23d (10.18ha), 24b (9.71ha), 24d (5.77ha) with *P. radiata* - these comp. are in the centre part of catchment
1939/40	Afforestation of compartments 9b (6.07ha), 11g (3.24ha, 50% in catch), 11h (2.83ha), 22d (8.50ha, 60% in catch), 22f (1.12ha), 22h (1.62ha), 24e (1.46ha), 24g (4.05ha), 24h (1.26ha) with *P. radiata*- these comp. are all on periphery of catchment
1940/41	Afforestation of compartment 14 (14.57ha) with *P. radiata* on south eastern side of catchment
Jan. 1944	Raingauge 11B commenced
1943 - 1946	Trees thinned to between 490 and 736 s.p.h.
1948 - 1956	Trees thinned to 368 s.p.h.
1960 - 1968	Trees thinned to 269 s.p.h.
Feb. 1976	Severe windfalls in compartments 24b, d, and e. 200 m³ timber removed
1979/80	Clearfelling commenced, and re-afforestation took place as compartments were clear felled
1982	Last compartments clear felled and re-afforested
Feb. 1986	A wild fire burnt down 80% of the catchment
1986/87/88	Re-afforestation of burnt areas- Compartments were re-numbered to provide distinction between the two tree age classes
11 Dec.1993	Wildfire burnt down 17ha of 6 year old trees in upper parts of catchment
1993 - 1996	Thinning of trees to between 490 and 750 s.p.h. in compartments not affected by previous fires

Biesievlei (27 ha)

Date	Treatment
February 1938	Catchment burnt
March 1938	Measuring of streamflow commenced (Kent waterlevel recorders)
January 1945	Raingauge 19A and 19B commenced
June 1948	Afforestation with *P. radiata* up to stream edge - no 20 m riparian zone left unplanted. Espacement 2.7 x 2.7 m, thus 1320 s.p.h.
1954	Trees thinned to 736 s.p.h.
Sept. 1964 - Mar. 1965	Trees thinned to 490 s.p.h.
Jul. - Oct. 1971	Trees thinned to 318 s.p.h.
1974	Trees thinned to 250 s.p.h.
Feb. - June 1984	Clear felled the bottom part of riparian zone
Aug. - Nov. 1984	Clear felled the upper part of riparian zone
May 1985 - Mar. 1986	Clearfelling rest of catchment
Mar - Jun 1986	Re-afforested with *P. radiata* to 1350 s.p.h
1995	Trees thinned to 736 s.p.h.

Tierkloof (and Waterval) (157 ha)

Date	Treatment
Sept. 1937	Raingauge 13A commenced.
Dec. 1938	Measuring of streamflow commenced
Jan. 1944	Raingauge 13B commenced
Apr. 1954	Indigenous vegetation cleared
Jun. 1956	Afforestation with *P. radiata*; espacement 2.7x2.7 m giving 1330 s.p.h.
5 May 1961	Streamflow measurement at Waterval weir commences
1966 - 1970	Trees thinned to between 595 and 865 s.p.h.
1975 - 1982	Trees thinned to between 296 and 592 s.p.h.
Sept. 1991	Waterval weir closed
May 1998 -	Clearfelling commenced

Lambrechtsbos B (65 ha)	
Date	**Treatment**
1942 - 1947	6.8 ha of compartments that fall within Lambrechtsbos B afforested
1 Apr. 1947	Measuring of streamflow commenced
April 1964	Whole unforested area of catchment (48.6 ha of total of 51.8 ha) clear felled and burnt (compartment 25)
1964 - 1965	Afforestation with *P. radiata*; espacement at 2.7x2.7m giving 1350 s.p.h.
1973	Trees thinned to 771 s.p.h.
1978	Trees thinned to 510 s.p.h.
1983	Trees thinned to 324 s.p.h.
1983 - 1989	The 6.8 ha of other compartments that fall within the boundaries of Lambrechtsbos B are clear felled and re-afforested

Lambrechtsbos A (31.2 ha)	
Date	**Treatment**
Jan. 1940	Raingauge 15A commenced gauging
Jan 1944	Raingauge 15B commenced gauging
1 Apr. 1947	Streamflow gauging commenced
Oct. 1971	Controlled burning of catchment and preparations for afforestation
1972	*Afforestation with P. radiata: espacement 2.7m x 2.7m giving 1350 s.p.h.*
1983	Trees thinned to 701 s.p.h
1987	Trees thinned to 443 s.p.h.
1990	Trees thinned to 250 s.p.h
March 1993	Weir temporarily closed

Langrivier (and Nerine) (245 ha)	
Date	**Treatment**
May 1938	Raingauge 14A commenced gauging
1 Jan. 1942	Streamflow gauging commenced at Langrivier
25 Dec. 1942	Whole catchment destroyed in wildfire
Jan. 1944	Raingauge 14B commenced gauging
Nov. 1948	Firebreak 800m wide burnt above catchment
19 Oct. 1966	Gauging of streamflow at Nerine weir commenced
Oct. 1974	About 8 ha burnt down while burning a firebreak
7 - 10 Sept. 1976	Langrivier weir - wall height increased by 3 ft.
5 Oct. 1987	Whole catchment burns down accidentally during burning of fire breaks
1 Apr. 1999	Whole catchment burnt down in back burn to save the plantation from wildfire

CATHEDRAL PEAK

Catchment II (190 ha)	
Date	**Treatment**
2 Aug. 1948	Raingauges 2A, 2C and 2BR commences
1 Oct. 1948	Streamflow measurement commences
1949	Controlled burning of catchment
1950/51	Afforestation of 68.5 ha (36%) with *Pinus patula*
1952/53	Afforestation of 32.5 ha (17%) with *P. patula*
1954/55	Afforestation of 9 ha (4.7%) with *P. patula*
1962/63	Afforestation of 5 ha (2,6%) with *P. patula*
1964/65	Afforestation of 27 ha (14%) with *P. patula*
1966	40% of Plantation thinned to 740 s.p.h.
1969	46% of Plantation thinned to 740 s.p.h.
1971/72	Defoliation of estimated 25% of trees by *Euproctis terminalis* (Pine brown tail moth)
1975/76	10% of Planted area thinned to 300 s.p.h.
1981 - 1984	Clearfelling of plantation; re-vegetated with *Eragrostis curvula*
Sept. 1988	Controlled burning of catchment to reduce fuel load
16 Sept. 1990	Wild fire burns through catchment; thereafter weir fills up with sediment after each storm

Catchment III (139 ha)	
Date	**Treatment**
Jul/Aug. 1950	Raingauges 3A and 3BR commences
1951	Controlled burning of catchment
1 Jun. 1952	Streamflow measurement commences
1953	Controlled burning of catchment
1956	Controlled burning of catchment
1957	Controlled burning of catchment
1958/59	Afforestation of 120 ha (86%) with *P. patula*
1964/65	41% of Plantation destroyed by wild fire, and replanted with *P. patula*
1969/70	25% of Plantation thinned by 40%
1972/73	Estimated 25% of trees defoliated by *E. terminalis*; 80% of plantation thinned to 300 s.p.h.
19 Sept. 1981	Severe wild fire burns down whole catchment; entire litter consumed. Thereafter weir fills up with sediment after each storm
1981/82	Catchment re-vegetated with *Eragrostis curvula*
May 1986	Controlled burning of catchment to reduce fuel load
16 Sept. 1990	Wild fire burns through catchment which again affects the sediment load from the catchment

Catchment IV (95 ha)	
Date	**Treatment**
Sept/Oct. 1949	Raingauges 4A, 4CR and 4BR commences
1 Oct. 1949	Streamflow measurement commences
1953 - 1990	Controlled bi-annual spring burning of catchment
1955, 1964 & 1972	Accidental burning of catchment

WITKLIP

Catchment III (160 ha)	
Date	**Treatment**
1948 - 1950	Afforestation of 54.2 % of catchment
1973 - 1974	5.8 ha (10.7 %) of plantation clear felled and re-planted
5 Mar. 1974	Raingauge RA2 (using Casella recorder) commences
21 Mar. 1975	Raingauge RB3 (using Casella recorder) commences
1974 - 1975	11.2 ha (20.6 %) of plantation thinned to stream 344 s.p.h.
Aug. 1975	Streamflow gauging commences using Belfort recorders
Jan. 1976	Leak in weir discovered
7 Sep. 1976	Leak in weir repaired
1981 - 1982	Thinned 5.8 ha (10.7 %) of plantation to 650 s.p.h
Apr - Jun. 1990	Partial clearfelling of catchment

Catchment V (108 ha)	
Date	**Treatment**
1942 - 1944	Afforestation of 46% of catchment
1955 - 1956	Afforestation of 8.8% of catchment
Jan. 1975	Raingauge RA5 (using Casella recorder) and streamflow measurement commences using Belfort recorder
9 Apr.1975	Upper part of catchment burnt
1982 - 1984	Clearfelling of plantation; now re-afforested right up to stream

Catchment VI (165 ha)	
Date	**Treatment**
1939 - 1944	Afforestation of 82% of catchment
Mar. 1974	Raingauges RA6 and RB6 commenced
Jan. 1975	Streamflow measurement commences using Belfort recorder
9 Apr.1975	Upper part of catchment burnt
1979 - 1981	Clearfelling of plantation; now re-afforested right up to stream

MOKOBULAAN

Catchment A (26.2 ha)	
Date	**Treatment**
01 Oct. 1956	Raingauges 1 and 2 commenced
06 Nov. 1956	Streamflow measurement commences with Ott water level recorders (later Belfort)
1957 - 1968	Controlled burning of catchment
Feb. 1969	100% Afforestation with *Eucalyptus grandis*: espacement 2.7 m x 2.7 m, giving 1330 s.p.h.
30 Apr. 1974	Plantation thinned to 750 s.p.h.
Oct.1974	Streamflow ceases for first time
Aug.- Nov. 1975	Streamflow ceased
Aug.- Dec. 1976	Streamflow ceased
May - Sept. 1977	Streamflow ceased
April 1978	Streamflow ceased completely even during rainy season
Jul. 1979	Plantation thinned to 418 s.p.h.
Jul. 1983	Plantation thinned to 250 s.p.h.
1985	Clearfelling of the whole catchment
Dec. 1988	First signs of streamflow
Apr. 1989	Upper area of catchment burnt
1990 - 1995	Continual streamflow, although some years ceases during winter. Consistency hampered by eucalypts regrowth
1998	Regrowth removed

Catchment B (34.6 ha)	
Date	**Treatment**
01 Oct. 1956	Raingauges 4, R3 and R4 commenced
06 Nov. 1956	Streamflow measurement commences with Ott water level recorders, (later Belfort)
1957 - 1970	Controlled burning of catchment
Jan.1971	100% Afforestation with *Pinus patula*: espacement 2.7m x 2.7m, giving 1370 s.p.h.
1978/79	The previously perennial stream starts flowing intermittently
Jul. 1979	Plantation thinned to 650 s.p.h.
Oct. 1980	Raingauge R8 commenced
1982 - 1995	Stream totally dried up
Dec1995 - Jan. 1996	Stream flows during period of excessive rain
Mar.- Nov. 1996	Clearfelling of catchment
17 Dec. 1996	A crack that developed in the dam wall was repaired
Nov. 1997	Sowing of grass seed to revert back to grassland
1997 -	Continual eradication of bugweed
1998 - 1 Mar. 1999	Stream flows after good rain, ceases in June

Catchment C (36.2 ha)	
Date	**Treatment**
01 Oct. 1956	Raingauges 5 and 6 commenced
06 Nov. 1956	Streamflow measurement commences with Ott water level recorders, (later Belfort; now automated)
1957 -	Controlled biennial winter burning of catchment (except 1992)
Jul. 1971	Streamflow ceased for this month
Feb. 1992	Streamflow ceased for this month, with no flow for the rest of the year
Feb. 1993	Streamflow started again, but stopped again in November
Jan. 1994	Streamflow started again, flowing intermittently and drying up in August
Aug. 1994 - Mar. 1995	No flow for this period
Apr. - Dec. 1995	Intermittent flow
Jul. - Aug 1998	Streamflow ceased during these months
12 May 1999	Controlled burning of catchment - clean burn

WESTFALIA

Catchment B (32.6 ha)	
Date	**Treatment**
01 Oct. 1972	Raingauges R1 and 1 commenced
16 Aug. 1974	Streamflow measurement commences using Belfort recorders
10 Nov.1990	Raingauge R1 closed and gauge 1 converted to monthly

Catchment D (39.6 ha)	
Date	**Treatment**
01 Oct. 1972	Raingauge 3 commenced
Jan. 1973	*Streamflow measurement commences using Belfort recorder*
16 Dec. 1974	Raingauge R3 commenced
Dec. 1980 - Jan. 1981	Riparian vegetation 20m either side of stream (total 4ha, 10 % of catchment) cut and left
Nov. 1981	Riparian regrowth slashed
Dec. 1982	Cleared (bulldozed) 83% of total area of indigenous forest; material stacked and burnt
Mar/Apr. 1983	Afforestation of 33 ha (83%) with *Eucalyptus grandis*; espacement 2.7 x 2.7 m, giving 1370 s.p.h.; riparian zone also afforested
1986	Plantation thinned to 700 s.p.h.
1989	Plantation thinned to 402 s.p.h.
Sep. 1989 - Oct. 1990	Stream flowed intermittently
Nov. 1990 - Aug. 1991	Continual streamflow for whole period
Aug. 1991 - Dec. 1991	Streamflow ceased
Aug. 1991	Plantation thinned to 298 s.p.h.
Dec. 1991 - Jan. 1992	Stream flowed again
Feb. 1992 - Nov. 1995	No streamflow
Aug. - Sep. 1995	Riparian zone clear felled (1294 m³ wood) and kept clear of invasives
Dec. 1995 -	Stream flowing continuously

Water Research Commission

PO Box 824, Pretoria, 0001, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www.wrc.org.za