THE HYDROLOGIC IMPACTS OF FORESTRY ON THE MAROONDAH CATCHMENTS

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COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Melbourne Water
Managing Our Water Resources

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PREFACE

CRC Project A2 "Development and evaluation of predictive tools for water production in natural, disturbed, and managed forests" aimed to quantify the relationship between catchment yield and forest management. Such knowledge is of immense importance to land and water managers for their planning scenarios.

The emphasis of Project A2 has been on the high-rainfall, ash forest areas, which comprise much of water supply catchments for the city of Melbourne. A notable feature of these catchments is that more than thirty years of hydrographic data have been collected in a research and experimental program, still being continued by Melbourne Water.

This report documents the analysis of the hydrographic data set by the CRC, an activity complementary to the extensive field work on tree water use and catchment model development in the A2 project. As such it forms an important addition to the previous analyses of the Melbourne Water data, because of the longer length of record now available, and the enhanced knowledge of water use processes in forests.

Fred Watson and Rob Vertessy (Project Leader), with strong input from the other named authors, have produced a report which has important ramifications for the management of forested catchments generally, but particularly for ash species.

I commend their work to you.

Russell Mein
Director
Cooperative Research Centre for Catchment Hydrology

Abstract

The effects of various forest treatments on forest water yield, low flow duration, and a range of other key forest hydrological variables were examined for the Maroondah experimental catchments in Victoria, Australia. The work follows more than three decades of hydrological data collection, analysis, and publication in Victoria's Mountain Ash forests, and attempts to synthesise some key data sets into a number of continuous descriptions of changes in hydrological variables in the decades immediately following forest regeneration.

The primary analysis was a rigorous statistical quantification of the effect of treatment on water yield in three catchment groups: Myrtle, Monda, and Coranderrk, the latter including Picaninny and Slip. Regressions of water yield data at treated catchments versus that at control catchments were formed. The chosen method used monthly data, driven by often short pre-treatment records, and involved accounting for heteroscedasticity, non-normality, and serial correlation in the data using log transformations, sinusoid regression terms, and a lag-one auto-regressive (AR1) model. Statistically significant treatment effects were observed in all cases. Both Myrtle and Picaninny responded to clearfelling with initial increases in yield in the 2-3 years following treatment, followed by more gradual decreases to significantly lower than pre-treatment values. It was uncertain whether a recovery back up to pre-treatment levels had commenced in either catchment (by 12 years of age for Myrtle, and 25 years of age for Picaninny). Water yield at Monda responded similarly to clearfelling in the first few years, but at the time when decreased water yield would be expected, the data were strongly affected by two Psyllid insect infestations causing dieback, and further periods of increased water yield. The three Monda catchments were initially regenerated at different seedling densities, but the infestations obscured any differences in water yield which may have resulted from this.

The data from all the subject catchments were able to be aligned along a single regeneration curve using a simple water balance model, which eliminated the influence of differences between the control catchments in comparisons between the paired catchment studies. A general evapotranspiration curve was fitted to the model results, and when subtracted from a mean precipitation value, was found to predict similar long term water yield patterns to the regionally-based Kuczera curve. Differences between the two curves centred on the inclusion of an initial increase in water yield, and a delayed recovery after water yield decline. Further analysis is required before the second of these differences, in particular, may be considered significant.

Results from secondary analyses were as follows. An analysis of changes in low flow duration (LFD) revealed that temporal patterns of LFD differed from water yield patterns only in the driest catchment (Picaninny), where low flows declined more than did overall yield. Declines in soil moisture were observed at Picaninny in the decade following forest clearing, matching our expectations based on water yield data. Forest growth at Picaninny appears to be peaking near the time of maximum water yield decline predicted by the general water yield curve, as would be expected. The growth data from Monda, however, clearly reveal the adverse effects of insect infestation on forest growth. Precipitation interception data at these two catchments essentially matches the growth data, which is also as expected because interception is largely controlled by leaf area index (LAI), itself an indicator of growth.

Acknowledgments

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1. Introduction

1.1 Aims

In south-east Australia in the early 1950s, the then Melbourne and Metropolitan Board of Works (now Melbourne Water) initiated an experimental hydrology programme designed to test the effects of various forestry treatments on long term water yield. A number of small experimental catchments were set up in the Ash forests of the Maroondah catchments in Victoria's Central Highlands near Healesville, 55 km north-east of Melbourne. Some of the catchments exhibited old growth forest, and some carried regrowth from wildfires in 1939. A variety of treatments such as clearfelling, patch cutting, artificial thinning, and planting at different stocking densities were applied in the 1970's and 1980's. Some of the catchments were left untreated and retained as controls.

The catchments were grouped according to the type of treatment. The groups were named Black Spur, Ettercon, Myrtle, Monda, and Coranderrk. Longer term results were presented for the Ettercon group by Benyon (1992), and for the Black Spur group by O'Shaughnessy and Jayasuriya (1994). A summary of the programme was presented by Vertessy et al. (1994). This report focuses on the Monda, Myrtle, and Coranderrk experiments.

The aim of this report was:

- to determine the changes in water yield (streamflow) in the Coranderrk, Monda and Myrtle catchments resulting from their respective forestry treatments,
- and to explain those changes, particularly with reference to measured changes in key components and parameters of the water balance, such as soil moisture, forest growth, and precipitation interception.

1.2 Background

Three key pieces of background information are pertinent. The first is a regional curve describing the long term decline and recovery of water yield with forest age (Section 1.2.1). This curve is pertinent to the first aim because changes in water yield in the experimental catchments are likely to be related to those represented by the regional curve. The second and third pieces of pertinent information are related curves describing the long term increase and subsequent decline in forest leaf area index (Section 1.2.2). The LAI curves are pertinent to the second aim because they are regional quantifications of changes in forest growth, and are likely to be reflected in the data from the experimental catchments.

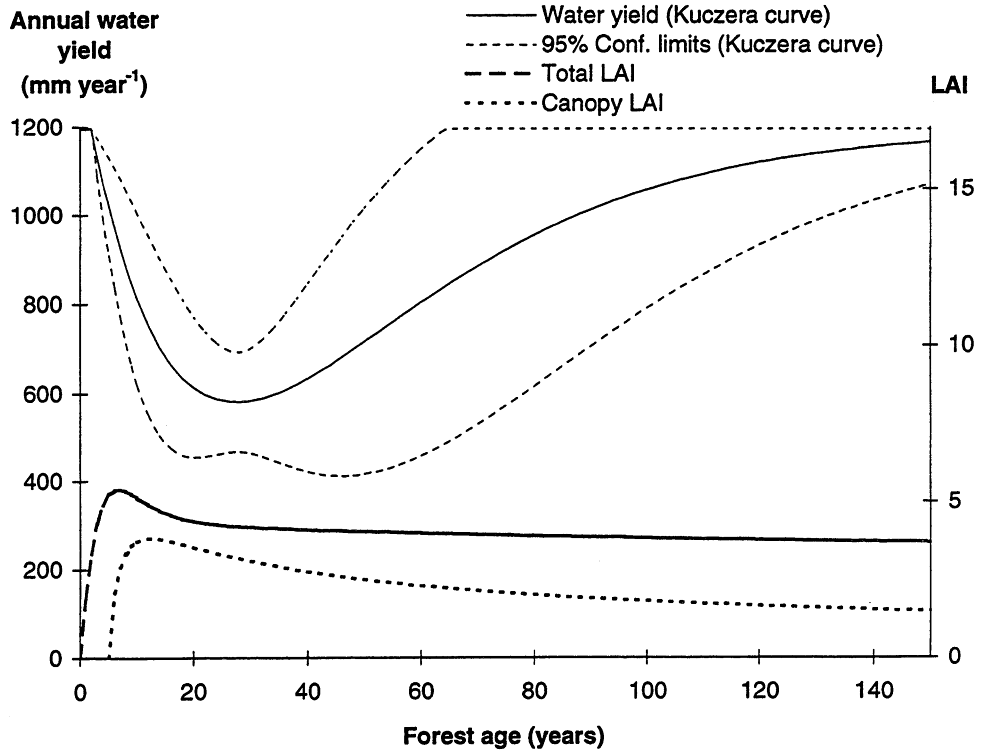


Figure 1: Long term changes in Mountain Ash forest water yield and leaf area index (LAI): the Kuczera curve (Kuczera, 1985, 1987) and the LAI curves of Watson and Vertessy (1996) and Watson et al. (1998).

1.2.1 The Kuczera curve

The Kuczera curve is a description of long term water yield from Ash forests, expressed as a function of forest age following regeneration (Kuczera, 1985, 1987). It is based on water yield data from a number of Melbourne's large water supply catchments in a 30 to 67 year period (depending on the catchment) spanning the 1939 wildfires, which burnt much of the catchments. The curve has two key parameters, L_{max} and $\log K$, which can be estimated for each catchment. A regional curve may be calculated using average values of these parameters calculated by Kuczera (1985, p. 120) as $L_{max} = 615$ mm and $\log K = -3.24$, and an additional estimate of the long term yield also estimated by Kuczera (1985, p. 149) as 1195 mm. This regional curve is shown in Figure 1. Note that this form of the curve is commonly reproduced, but was never actually presented as such by Kuczera. Data from regrowth forests were available to Kuczera only for forests less than 42 years old, and so the recovery to old growth yield after 42 years of age is an assumed pattern and is not based on direct observations. The curve as shown assumes a pure Mountain Ash forest.

From age zero, the curve predicts a decline in water yield to near half its old-growth value by 20 to 30 years of age. Following this, a gradual rise in water yield to the old-growth value over the next 50 to 100 years is predicted.

The curve represents the effect on water yield of regenerating an old growth forest (either by wildfire or logging), and therefore serves as the most appropriate estimation of what may be expected to occur in clearfelled experimental catchments such as Myrtle and Picaninny (from the Coranderrk group). It also serves as a reference point for catchments subject to other treatments. Of course, such reference should be associated with due consideration of the difference in scale between the experimental catchments and the larger catchments used in Kuczera's analysis, and in the accompanying climatic differences.

1.2.2 Leaf area index curves

The experimental work at Maroondah has shown that the decline in water yield in regrowth Ash forests can be explained by concomitant increases in transpiration and interception of precipitation (Vertessy et al., 1994; Vertessy et al., 1998; Haydon et al., 1996). Both of these are dependent upon the leaf area index (LAI) of the forest.

Recently, long term curves have been put forward expressing the dependence of both LAI and interception on forest age (Watson and Vertessy, 1996; Watson et al., 1998; Watson, 1998).

Two LAI curves are relevant: one for the LAI of just the canopy species, Mountain Ash; and the other for the total LAI of the forest, including understorey species. A canopy LAI curve was described by Watson and Vertessy (1996) based on a combination of direct, destructive LAI measurements and stem diameter measurements. Subsequently, a total LAI curve was put forward by Watson et al. (1998) and Watson (1998) based on a combination of ground based measurements using light meters and satellite based measurements. Both curves are shown in Figure 1 and predict a rapid increase in LAI from zero at age zero to a peak at about 10 years of age. This is followed by a gradual decline to a long term climax value in the case of total LAI, and possibly to zero in the case of canopy LAI.

LAI is an indicator of forest growth, and so the stated LAI curves offer a reference upon which may be based expectations of forest growth patterns in the experimental catchments, as discussed later in this report. Once again, due consideration to differences in scale and climate should be given.

An interesting feature of the curves shown in Figure 1 is the difference in timing between the dip in the water yield curve (at 10 to 20 years of age) and the peak in the LAI curves (at about 10 years of age). An ancillary aim of this report was to provide information on forest water balance dynamics which may help to explain this difference.

1.3 Report outline

Following a chapter summarising the catchment experiments, their histories and publications, individual chapters are given on each of the major analyses. Chapter 3 presents a statistical analysis of the effects of forest treatment on water yield in the subject catchments. This is followed by a related chapter where a simple model of long term water balance is constructed, in order that the water yield data from all the catchments may be combined together. Chapter 5 examines the question of whether important statistics such as low flow duration respond to forest treatment in the same way as overall water yield. The next three chapters examine some key explanatory data required for a full description of changes in forest water balance following treatment. The first of these, Chapter 6, examines changes in soil moisture during early forest regrowth. Chapter 7 describes the response of forest growth to treatment, as well as insect infestation, and Chapter 8 describes changes in precipitation interception. In each case, a detailed summary of all available data is presented. A report summary is given in the final chapter.

2. The Maroondah experimental catchments

2.1 Introduction

This section briefly introduces the Maroondah experiments and experimental catchments, and refers the reader to a number of reports and summary publications which have described their progress to date. A number of additional pieces of background information are also noted, relating to possible extraneous influences on streamflow such as weir leakage, and insect infestation.

2.2 General

The Maroondah catchments are located about 55 km north east of Melbourne in Victoria, Australia (Figure 2). They comprise five water supply catchments and 18 small experimental catchments (Figure 3). The area has an extensive research and publication history, most recently summarised by Vertessy et al. (1998). The terrain is steep and mountainous and the climate is wet, with mean annual precipitation ranging from 1100 mm to 2800 mm across the area (Watson, 1998). The area is entirely forested, predominantly by tall stands of the wet sclerophyll species Mountain Ash (*Eucalyptus regnans*) and Alpine Ash (*E. delegatensis*), but also with dry sclerophyll species such as Messmate on the drier slopes. The geology is acid volcanic and the soils are deep gradational clay loams.

The experimental catchments at Coranderrk and North Maroondah were established in the 1950's and 1960's respectively. The reasoning behind their establishment is best summarised in a 'Status Report' by O'Shaughnessy and Jayasuriya (1991). The history of the catchments is summarised in the sections below. These are supplemented by detailed catchment-by-catchment summaries in Figure 4 and Table 1.

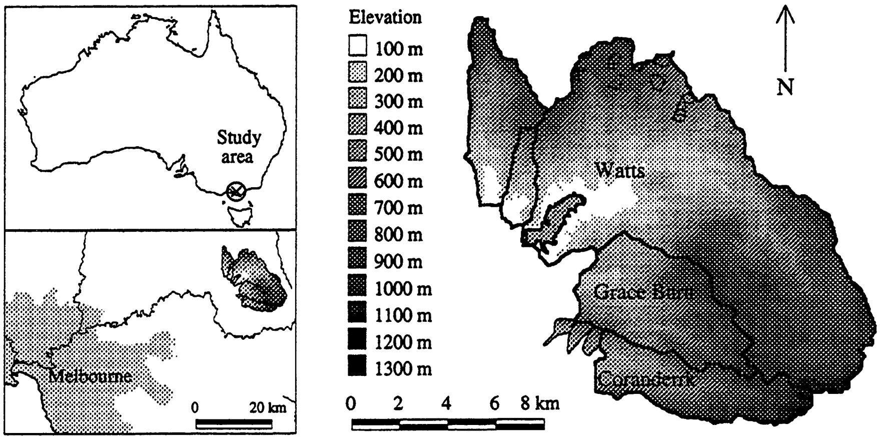


Figure 2: Location and topography of the Maroondah study area near Melbourne, Victoria, Australia.

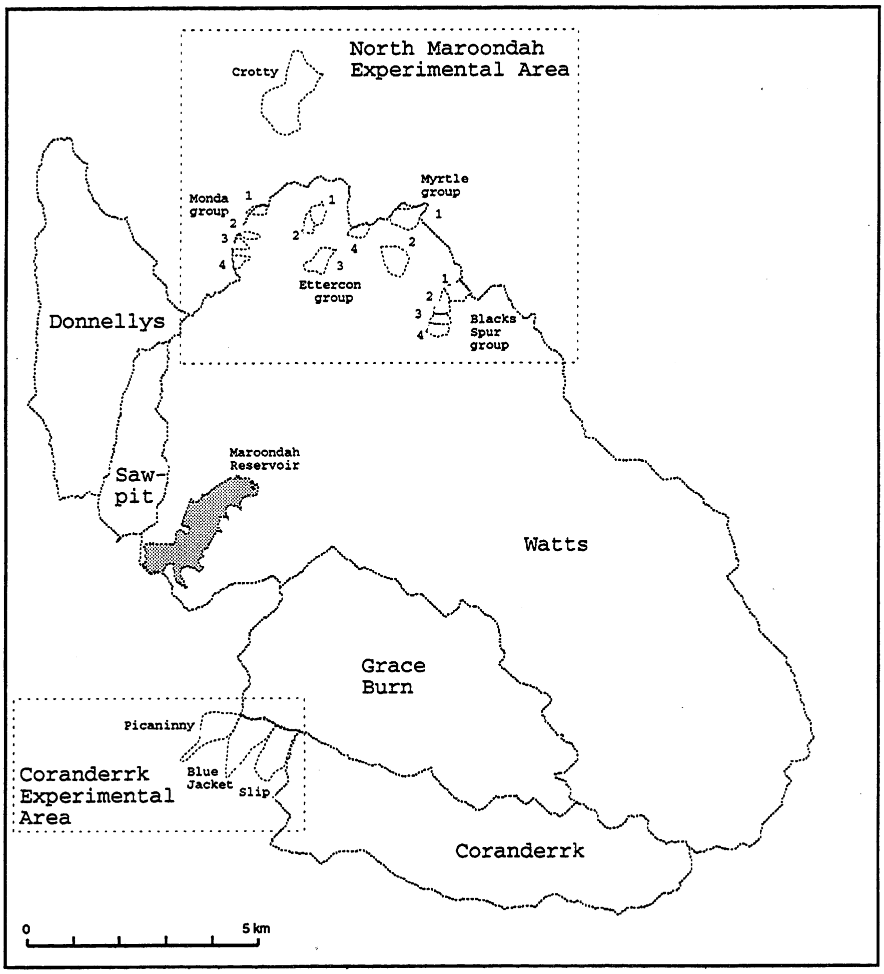
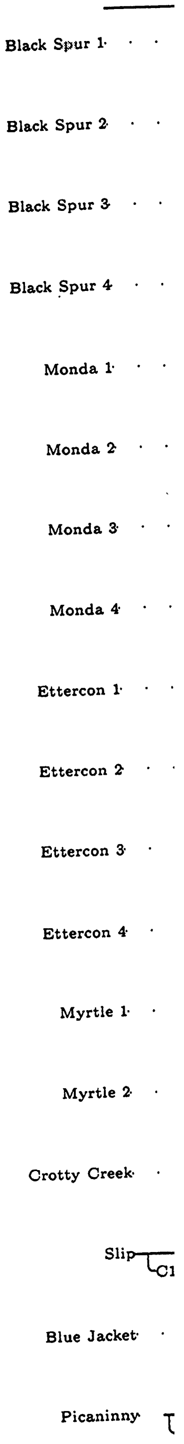


Figure 3: Experimental and water supply catchments within the Maroondah study area.



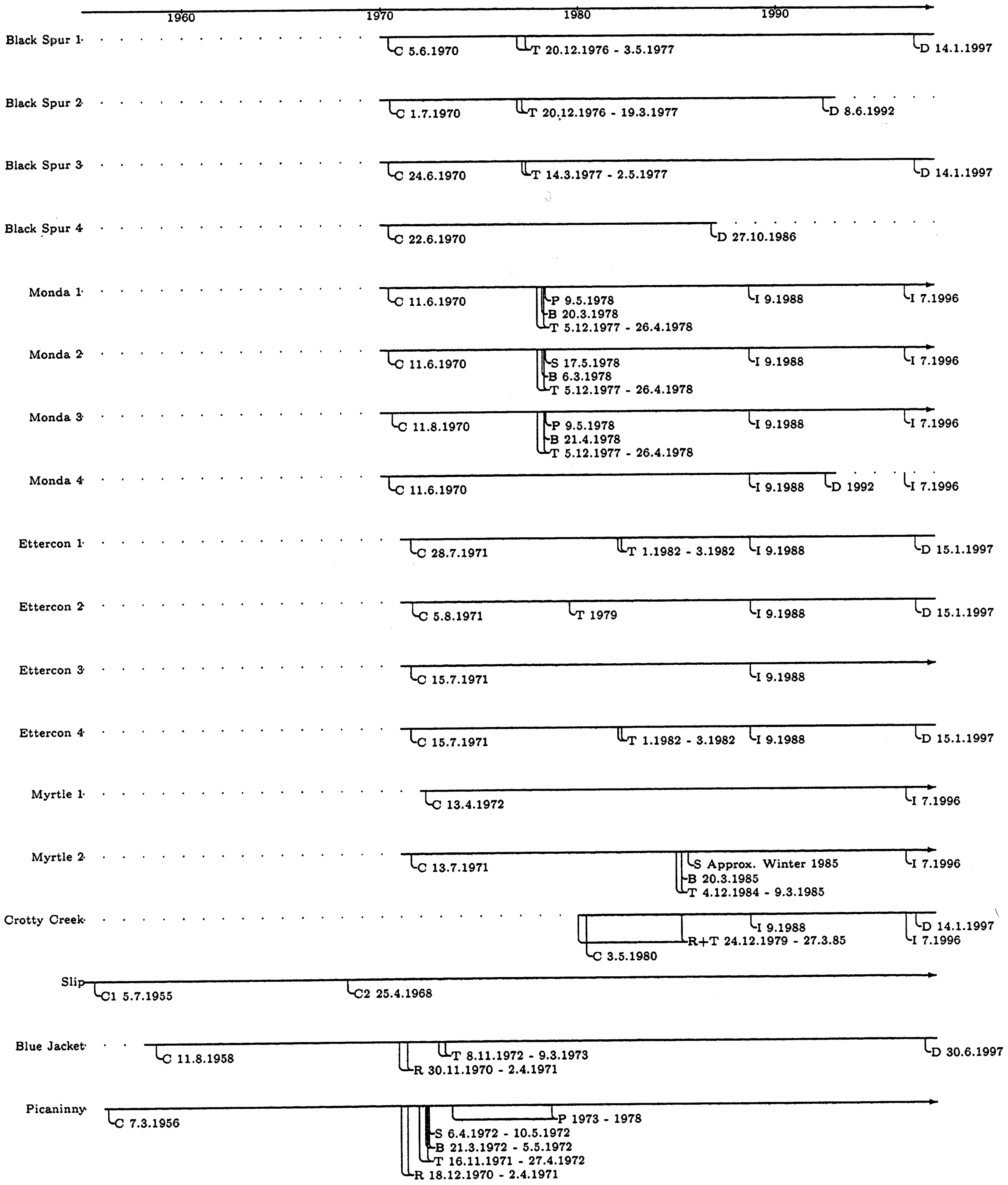


Figure 4: Time lines for each of the experimental catchments.
C = Commencement of record; R = Roading; T = Treatment; B = Burning; S = Seeded; P = Planted; I = Infested with Psyllids; D = Decommissioned. References: Howard and O'Shaughnessy, 1971, p. 115; Fiske et al., 1977, p. 82.; Langford and O'Shaughnessy, 1977, p. 271; O'Shaughnessy, 1979, p. 61; O'Shaughnessy, 1980; Ord, 1985; Benyon, 1992, p. 11; O'Shaughnessy, 1994, pp. 13-24

Table 1: Experimental catchment histories. Key to references: HO71 = Howard and O'Shaughnessy, 1971; LO77 = Langford and O'Shaughnessy, 1977; O79 = O'Shaughnessy, 1979; LO80 = Langford and O'Shaughnessy, 1980; O81 = O'Shaughnessy et al., 1981; O85 = Ord, 1985; OJ91 = O'Shaughnessy and Jayasuriya, 1991; B92 = Benyon, 1992; O93 = O'Shaughnessy et al., 1993.

Name	Treatment/purpose	Area (ha)	Dominant pre-treatment cover	Published desciptions of change in water yield	References
Black Spur 1	54% patch cut	16.97	1939 *E. regnans*	Persistent 20% inc. (OJ91)	LO77
Black Spur 2	33% uniform thinning	9.63	1939 *E. regnans*	Minor impact (OJ91)	LO77
Black Spur 3	50% uniform thinning	7.73	1939 *E. regnans*	Persistent 20% inc. (OJ91)	LO77
Black Spur 4	None (control)	9.81	1939 *E. regnans*	Control	LO77
Monda 1	79% clearfelled & regenerated with 2000 seedlings/ha	6.31	1939 *E. regnans*	Large initial inc. (OJ91)	LO77, O79
Monda 2	75% clearfelled & regenerated with 5000 seedlings/ha	3.98	1939 *E. regnans*	Large initial inc. (OJ91)	LO77, O79
Monda 3	80% clearfelled & regenerated with 500 seedlings/ha	7.25	1939 *E. regnans*	Large initial inc. (OJ91)	LO77, O79
Monda 4	None (control)	6.31	1939 *E. regnans*	Control	LO77, O79
Ettercon 1	39% strip thinned	11.67	1939 *E. regnans*	Persistent 20% inc. (OJ91)	LO77, B92
Ettercon 2	Understorey removed	8.83	1939 *E. regnans*	Not described yet	LO77, B92
Ettercon 3	None (control)	15.01	1939 *E. regnans*	Control	LO77, B92
Ettercon 4	35% strip thinned	9.03	1939 *E. regnans*	Persistent 20% inc. (OJ91)	LO77, B92
Myrtle 1	None (control)	25.21	(c). 1759 *E. regnans*	Control	LO77
Myrtle 2	74% clearfelled	30.48	(c). 1759 *E. regnans*	Inc. for 4 yrs (OJ91)	LO77, O85
Crotty	50% strip thinned	122.33	1939 *E. regnans*	Persistent 25% inc. (OJ91)	O81, O93
Slip	None (control)	62.3	(c). 1850 *E. regnans*	Control	HO71, LO80
Blue Jacket	Selective cut	64.8	(c). 1850 *E. regnans* & *E. obliqua*	> 30% inc. for c. 10 yrs, then > 15% dec. (OJ91)	HO71, LO80
Picaninny	78% Clearfelled	52.8	(c). 1850 *E. regnans* & *E. obliqua*	> 100% inc. for c. 10 yrs, then > 50% dec. (OJ91)	HO71, LO80

2.3 Coranderrk

Coranderrk is a local Aboriginal place name. Coranderrk Creek flows westward along the southern section of the Maroondah water supply catchment area. It contains a major water supply diversion weir defining the Coranderrk catchment (19.44 km^2). The Coranderrk experimental catchments are three smaller catchments that drain southwards into Coranderrk Creek below its water supply diversion weir. The catchments are named Picaninny (52.8 ha), Blue Jacket (64.8 ha), and Slip (62.3 ha) and each contains a small gauging weir.

Two reports on Coranderrk are completed, and a third remains un-completed. The first was the 'First Progress Report: Coranderrk' (Howard and O'Shaughnessy, 1971) which described the area and the planned treatments, and reported early analysis of data on precipitation, soil moisture, streamflow, and water quality. This was followed by a more comprehensive document, the 'Second Progress Report: Coranderrk' (Langford and O'Shaughnessy, 1980b), which reported on the experimental treatments applied in the early 1970's and post-treatment monitoring. Detailed descriptions were also given of precipitation, interception, soil moisture, streamflow, and water quality data. A number of analytical techniques were introduced to assess the hydrological effects of the treatments - including regression against rainfall data, regression against control catchment streamflow, and a simple water balance model (the SDI model) calibrated on pre-treatment streamflow. The 'Third Progress Report: Coranderrk' was never completed, although chapters were partially written on continued data collection, analysis of precipitation and interception data, and the effects of treatment on streamflow [1]. Some auxiliary reports were also produced, including 'A Study of the Coranderrk Soils' (Langford and O'Shaughnessy, 1980a).

2.4 North Maroondah

At the northern end of the Maroondah water supply catchment area lies the North Maroondah experimental area, which contains a further 15 small experimental catchments divided into five groups based on the type of experimental treatments which were applied. These groups are Monda: (4 catchments), Ettercon (4 catchments), Myrtle (2 catchments), Black Spur (4 catchments), and Crotty Creek (1 catchment).

The 'First Progress Report: North Maroondah' (Langford and O'Shaughnessy, 1977) is a comprehensive document which describes the catchments, as well as detailed analysis of climate, soil moisture, and streamflow data. Initial modelling of streamflow using regression models and a water balance model (the SDI model) applied to the Black Spur group was also presented, as were

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[1] Pers. comm., Shane Haydon, Melbourne Water

the associated thinning and patch cut treatments. The 'Second Progress Report: North Maroondah' (Langford and O'Shaughnessy, 1979a) is smaller document dealing only with the Monda group. It describes initial regression and water balance modelling for the Monda catchments, as well as the associated treatments involving clearfelling and re-seeding at different densities. The Crotty Creek Project was described in two separate Progress Reports (O'Shaughnessy et al., 1981, 1993). The first report introduced the Crotty Creek catchment and early data collection, with some streamflow regression models constructed using the other North Maroondah catchments as control. The second report described the strip thinning treatment and analysed its effects on streamflow yield and streamflow statistics. A separate report was also produced for the Ettercon group (Benyon, 1992), with a description of strip thinning treatments and a detailed analysis of the effects of this on forest growth. Effects on streamflow were not analysed. The experiment at the Myrtle group, where an old-growth catchment was clearfelled, has not been written up in detail. The implementation of harvesting at Myrtle 2 was described by Ord (1985).

2.5 Extraneous influences on streamflow and streamflow gauging

The intention with all of the experimental catchments was to apply well defined treatments to the forest, and to observe the effects on hydrology. Table 1 summarises these treatments. However, various extraneous influences have also occurred and are elaborated upon here.

Slip weir problems The first weir installed at Slip creek was deemed unsuitable due to leakage, inappropriate stilling, and doubtful strength. A second weir was built and commissioned in April 1968. Data from the first weir are not used here.

Monda 4 boundary problems Modelling and water balance studies indicates that the Monda 4 catchment collects water from area outside its surface-defined boundary (Duncan et al., 1979, p. 35). Monda 4 was intended to be the control catchment for the Monda group, but has been decommissioned. Ettercon 3 is now considered to be the most suitable control for the Monda group and is thus used here.

Picaninny regrowth problems Regrowth after clearing at Picaninny was not as vigorous as is often the case after natural burning of Ash and mixed species forest (O'Shaughnessy, 1980). Drought, browsing by Wallabies, and weed infestation hampered regrowth, which was augmented by planting and various Wallaby-deterrent measures. In some parts of Picaninny, it was not until about 1977 or five years after clearing, that significant regrowth began.

1988 Psyllid infestations In October 1988, Psyllids infested the Monda, Ettercon, and Crotty catchments. The insects were identified as the lerp stage of *Hyalinaspis semi-spherula* and were observed to have caused severe crown dieback in a number of catchments. Subsequent analysis of the infestation involved: mapping of the extent of the infestation over the North Maroondah area, establishing that the species was not the same as that previously observed in the Thomson catchment and is unusual in *E. regnans* forest, and repeated photography of various sites [2]. It was estimated that the 'effects' of the infestation lasted one year. Catchments known to be affected by this event are marked in Figure 4 on Page 7.

1996 Psyllid infestations In July 1996, Psyllid infestation occurred again, this time by *Cardiaspina bilobata*, lerps which had been found in the Thomson catchment in 1990, Upper Yarra in 1991, O'Shannassy in 1992, and Marysville in 1994. Catchments known to be affected by this event are also marked in Figure 4.

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[2] Pers. comm., J. Snodgrass, Melbourne Water, Healesville.

3. Change in water yield

3.1 Introduction

This section aims to quantify the changes in water yield that have been observed in each of the experimental catchments in response to forest treatments. It commences with a review of past approaches to this problem, and then presents a rigorous statistical method designed to suit the occasionally short pre-treatment records associated with the present study. The Myrtle catchment pair is used as an example case to describe our analytical method. This method is then applied to the other subject catchments, culminating in a discussion of results.

3.2 Review

3.2.1 Methodology

There are two commonly used methods for assessing the impact of forestry treatments on water yield. One is the paired catchment approach, where the streamflow record from a control catchment streamflow is used to predict the streamflow of a treated catchment based on a regression relationship between the two. In the post-treatment period, residuals from the prediction are assumed to be a measure of the effect of treatment. The other method uses water balance models driven by climatic inputs such as precipitation and temperature. These are calibrated on pre-treatment streamflow, and then used to predict post-treatment flow. Once again, the post-treatment residuals are assumed to be a measure of the effect of treatment. The choice between these two approaches depends on whether climate data such as precipitation and temperature are better able to be used to predict streamflow at the subject catchment than the streamflow record from a control catchment (assuming one exists). This is determined either by experience, or by trial and error. The two methods are examined in more detail below.

Paired catchment methods

The paired catchment approach is the most popular, being the foundation of many of the studies cited in the key reviews of forestry impacts on hydrology (Bosch and Hewlett, 1982; Whitehead and Robinson, 1993; Stednick, 1996). Recent Australian studies have used linear regression on annual flows (Jayasuriya and O'Shaughnessy, 1988, 1990; Bren and Papworth, 1991, 1993; Cornish, 1993; Jayasuriya et al., 1993; Nandakumar, 1993; Nandakumar and Mein, 1993). Monthly data are less commonly used because they are generally serially correlated and therefore violate the assumption of independent data necessary for statistical characterisation of the results of regression by least squares. The work of Scott and Lesch (1997) in South Africa is an exception. These authors included both streamflow from a control catchment *and* precipitation data as independent variables in a monthly multiple linear regression.

The pre-treatment period in paired catchment studies is often short, which limits the strength of regression analysis. The advantage of using monthly data is that twelve times more data points are available than in analysis of annual data. Techniques for accommodating the associated serial correlation are available, such as explicit modelling of seasonal variations using, for example, sine curves (Hirsch et al., 1991; Helsel and Hirsch, 1992), and modelling of regression residuals as auto-regressive moving-average (ARMA) processes (Kuczera and Mein, 1982; Kuczera, 1983a, b; Holder, 1985; Salas, 1993).

Residuals from paired catchment regressions tend to be heteroscedastic (more variable with higher flow), which also violates the assumptions necessary for valid statistical characterisation of regression results. This can be avoided by first transforming the data by taking the logs (Hirsch, 1982; Alley and Burns, 1983; Stedinger 1980, 1981), or more generally, by applying a Box-Cox transformation (Kuczera and Mein, 1982; Kuczera, 1983a, b; Clarke, 1994).

Whilst an *individual* estimate of streamflow derived from least squares regression against a control catchment is the best estimate given the control catchment data, a group of such estimates is biased in its variance (Hirsch, 1982). A set of predictions based on least squares regression will be less variable than the corresponding set of observations. A number of 'maintenance of variance extension' (MOVE) procedures have been developed to correct this (Matalas and Jacobs, 1964; Hirsch, 1982; Alley and Burns, 1983; Vogel and Stedinger, 1985; Grygier and Stedinger, 1989; Vogel and Kroll, 1991). However, these procedures have not been employed in paired catchment studies and no attention has been given to whether or not under-estimated variance in predicted post-treatment streamflow affects the outcomes of forestry impacts studies.

Climate driven models

The simplest climate driven models include simple linear regression and multiple linear regression of streamflow against precipitation from one or more sites. Such an approach underpinned Langford's (1974, 1976) and Kuczera's (1985, 1987) analyses of long term changes in annual water yield following wildfire in the Melbourne water supply catchments. The method undoubtedly suffers from spatial heterogeneity in rainfall fields and the inability of temporal signals in catchment precipitation to be inferred from a small number of precipitation gauges (see for example Watson, 1998). However, in the absence of suitable control catchments (generally the case in very long term studies), it is one of the only alternatives.

Simple water balance models have also been used. The lumped conceptual models SDI and CATPRO have been used with monthly data by Melbourne Water within the study area to assess the effects of forest treatment on streamflow (Langford et al., 1977, 1978, 1982; Kuczera and Mein, 1982; Kuczera, 1983a, b, 1984, 1988a,b; Jayasuriya and O'Shaughnessy, 1988, 1990; Haydon and Jayasuriya, 1993; Kuczera et al., 1993). The approach taken is to calibrate the model on pre-treatment flows, apply it to post-treatment flows, and examine the residuals. The model yields similar, if slightly lower, performance measures to the control catchment approach, and whilst more complex, it is cited to have the advantage of offering information about catchment processes through the values of calibrated model parameters. It should be noted that, typically, the SDI applications cited used a single calibration for all the experimental catchments. This generality places SDI at a slight disadvantage relative to regression based methods which are implemented on a per-catchment basis.

More recently, the daily lumped conceptual model IHACRES has been applied to the same catchments (Post and Jakeman, 1996, 1998; Post et al., 1993, 1996, 1998). The approach these authors used was to infer treatment effects from changes in calibrated model parameters over time. Specifically, the streamflow record was broken up into about 20 successive one to two year periods spanning the treatment. The model was calibrated separately on each period, and a parameter which determined the ratio of streamflow to precipitation (the runoff coefficient) was plotted against time. After treatment, the calibrated value of this parameter increased and then decreased, suggesting that the effect of forest treatment was an increase in streamflow followed by a decrease. There are some limitations of the approach. No use is apparent of the daily time step of the model. It could be simplified using a monthly time step and an elimination of the separation of quickflow and slow flow. Additionally, Post et al. refrain from deriving error estimates and hence from placing confidence limits around their analyses of treatment effects.

3.3 Streamflow data

Streamflow data are available from each of the experimental catchments for the periods summarised in Figure 4. The three Coranderrk records (Slip, Blue Jacket, and Picaninny) commenced in the 1950's, although, as noted earlier, the first weir at Slip Creek was considered unreliable. The record from the replacement weir begins in 1968. The fourteen North Maroondah records commence in the early seventies, and the Crotty Creek record commences in 1980. For the present study, data were obtained up until late 1997. A number of catchments have been discontinued for reasons including: conclusion of experiment (Ettercon and Black Spur groups), limited experimental value (Blue Jacket), and interference from surrounding catchments (Monda 4).

3.4 Method

Methods based on linear regression against control catchments were chosen as the basis for analysing the effects of forest treatment on water yield. This is because such methods are more simply stated than climate based modelling methods such as SDI and IHACRES, yet confer similar or better predictive capability.

Monthly rather than annual data were used because some of the catchments (Slip Creek in particular) had short pre-treatment records. This introduced additional complexity associated with seasonal trends in monthly data, but enabled a greater amount of information to be used for a given record extent.

3.4.1 Initial linear regression

The Myrtle group (Myrtle 1 and 2) was used to illustrate the details of the method. The raw records measure flow in litres per second. For the present study, they were converted to millimetres per day using the catchment areas given in the early progress reports (Moran, 1980, p. 76; Moran and O'Shaughnessy, 1977, p. 54; O'Shaughnessy et al., 1981, p. 13). Millimetres per *month* were not used because each month has a different number of days and therefore represents a different period of accumulation. Figure 5 shows the hydrographs from the two catchments. Clearly, runoff from the two catchments is highly correlated. Figure 6 plots one against the other, indicating that the relationship between the two appears slightly non-linear.

The period for which data are available from both Myrtle 1 and 2 commences in May 1972, and treatment began at Myrtle 2 in December 1984. Thus there were 151 months of pre-treatment data with which to calibrate a predictive model of post-treatment flow at Myrtle 2. An analysis based on annual data would have been adequate in this case, but could not have been applied to the other catchments examined in this study.

Initially, a linear regression was formed between the two runoff records with coefficients determined by ordinary least squares (OLS), yielding the equation:

$$\hat{y} = 0.593 + 0.903\,x \tag{1}$$

$$r^2 = 0.934,\ n = 151$$

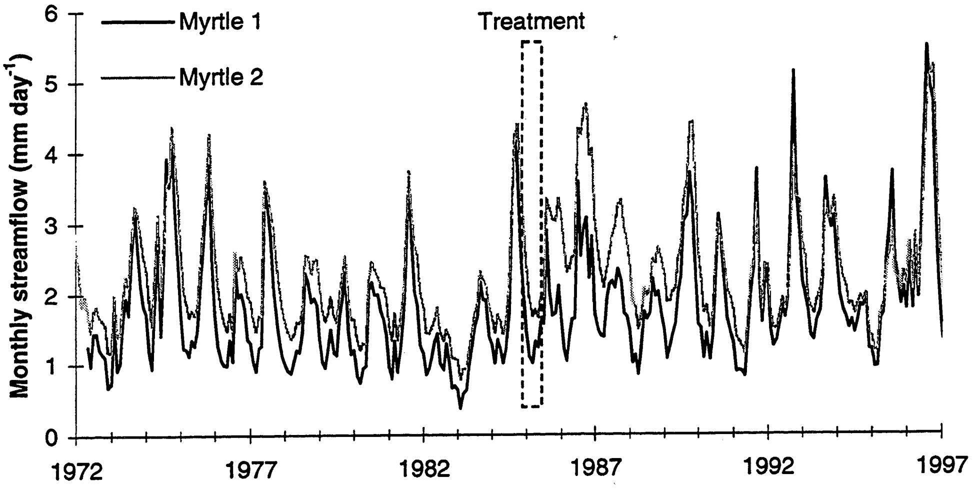

Figure 5: Monthly hydrographs at Myrtle 1 and 2.

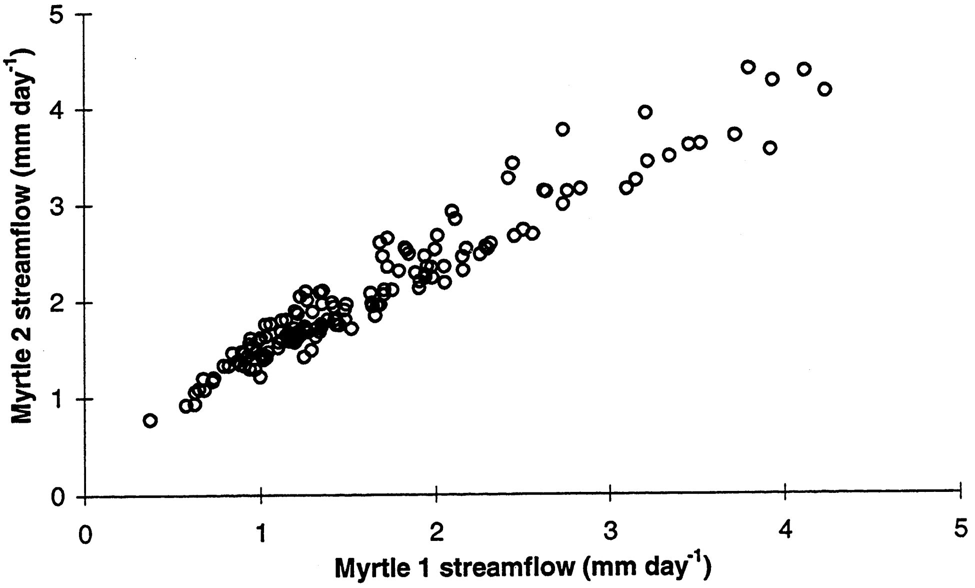

Figure 6: Monthly pre-treatment flows at Myrtle 1 and 2 plotted against each other.

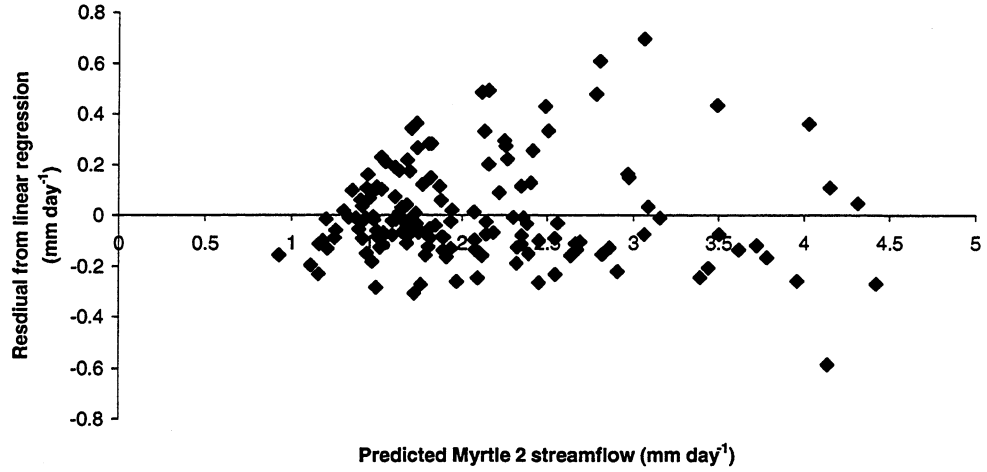

Figure 7: Residuals from linear regression plotted against predicted flow.

where $\hat{y}$ is the flow (in mm day^{-1}) at the treated catchment (Myrtle 2) and x is the flow at the control catchment (Myrtle 1).

3.4.2 Statistical constraints

In order to be able to place confidence limits around the predictions made by a model such as this, the following requirements must be met:

- samples uniformly distributed with respect to predicted values
- residuals homoscedastic (i.e. variance of residuals constant with respect to predicted values)
- residuals independent (no auto-correlation, serial correlation, dependence of one residual upon another)
- residuals normally distributed
- residuals aperiodic, stationary, and unbiased

These requirements are checked in turn in the following analysis.

Figure 7 shows a plot of the residuals against the predicted flow and reveals significant heteroscedasticity (the variance of the residuals increases with flow). This indicates that some transformation of the raw data is necessary.

3.4.3 Log/log regression

A log transformation was chosen as the simplest means of correcting non-uniformity and heteroscedasticity. Generalising to Box-Cox transformations

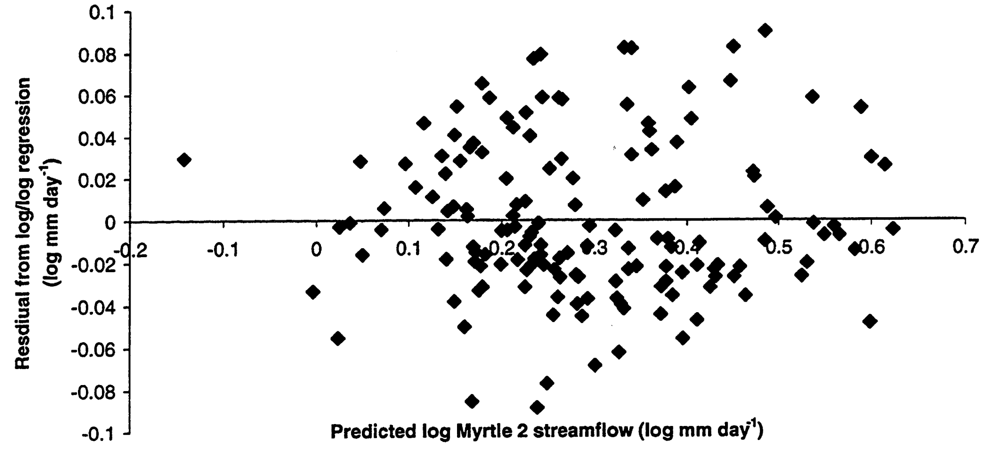

Figure 8: Residuals from log/log regression plotted against predicted log flow.

would also be possible. Reforming the regression with log transformed data yielded:

$$\log \hat{y} = 0.169 + 0.724 \log x \qquad (2)$$

$$r^2 = 0.939,\ n = 151$$

with homoscedastic residuals as shown in Figure 8.

The time series of residuals from the log/log regression (Figure 9) suggests a strong seasonality or periodicity of residuals. This is confirmed by plotting the residuals against the month of the year as in Figure 10, which clearly shows a tendency toward higher residuals in the first half of the year and lower residuals in the latter half of the year. An alternative perspective is gained by examining the correlogram of the residuals shown in Figure 11, which reveals strong positive autocorrelation of monthly residuals at lags near one and twelve months, and strong negative autocorrelation at lags near six and eighteen months.

It should be explained that seasonality implies serial correlation, but that the reverse it not necessarily so. Serial correlation can occur in data with no periodic component. Therefore, removal of seasonality (de-seasonalisation) and removal of serial correlation are treated as successive but separate tasks here.

3.4.4 Allowing for seasonality - log/log/sine regression

There are a number of ways to deal with the seasonality revealed in Figure 11. Salas (1993) suggested standardising each residual by the mean and

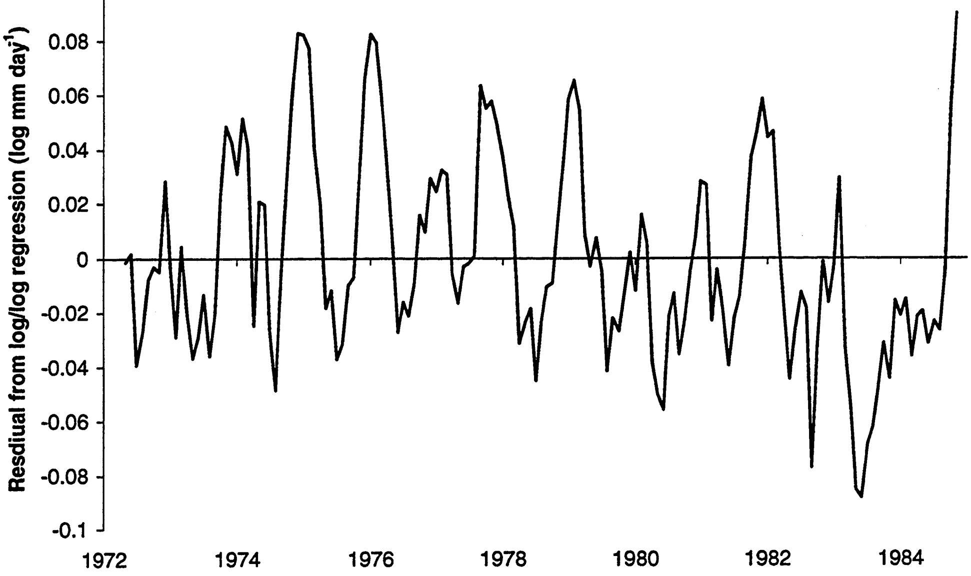

Figure 9: Time series of residuals from log/log regression, showing a seasonal trend.

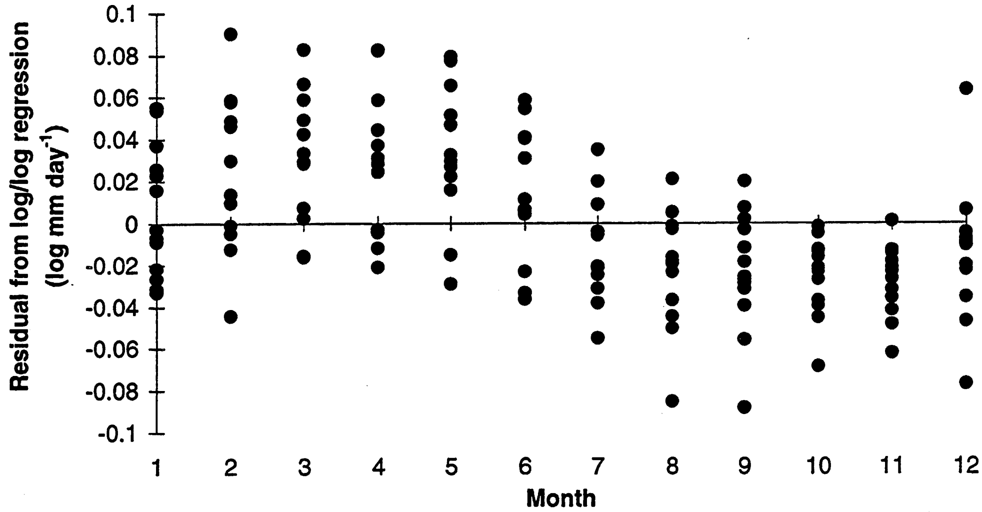

Figure 10: Residuals from log/log regression plotted by month, confirming a seasonal trend.

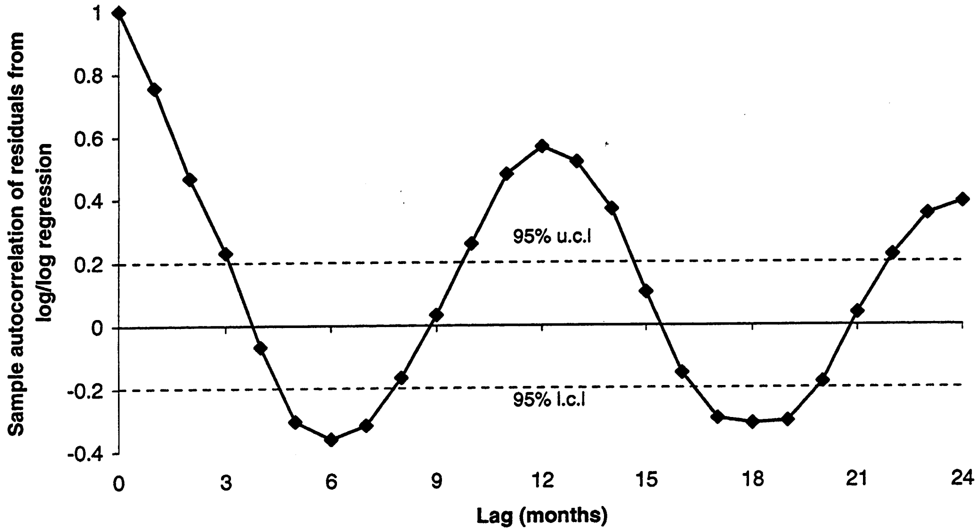

Figure 11: Correlogram of residuals from log/log regression, showing large positive and negative serial correlation aligned annually and semi-annually.

standard deviation of residuals for its respective month. This was trialed and led to acceptable de-seasonalisation, but suffers from the same problem of analysing annual data from short pre-treatment records. Insufficient data points are available for calculating monthly means and standard deviations. It also involves a loss of information, in that the method does not make use of the fact that the mean residual for a given month is usually similar to that for neighbouring months (this can be seen from Figure 10).

Instead, the problem was re-cast as a multiple regression on log transformed data as before, but including sinusoidal trigonometric terms as additional independent variables (after Box and Jenkins, 1976; and Helsel and Hirsch, 1992). This explicitly assumes a sinusoidal seasonal trend in the relationship between streamflow at the two catchments. It requires only two additional parameters, as opposed to the 24 means and standard deviations above. Thus, the following multiple regression was formed:

$$\log \hat{y} = 0.161 + 0.777\ \log x + 0.021 \sin \frac{2\pi\omega}{12} + 0.031 \cos \frac{2\pi\omega}{12} \qquad (3)$$

$$r^2 = 0.965,\ n = 151$$

where ω is the month of the year.

Figure 12 plots a time series of the residuals of this new 'log/log/sine' model. The apparent lack of periodicity suggests that the seasonal component is well accounted for by the model, but there remain lengthy runs of either positive or negative residuals, implying that serial correlation is still present. This is

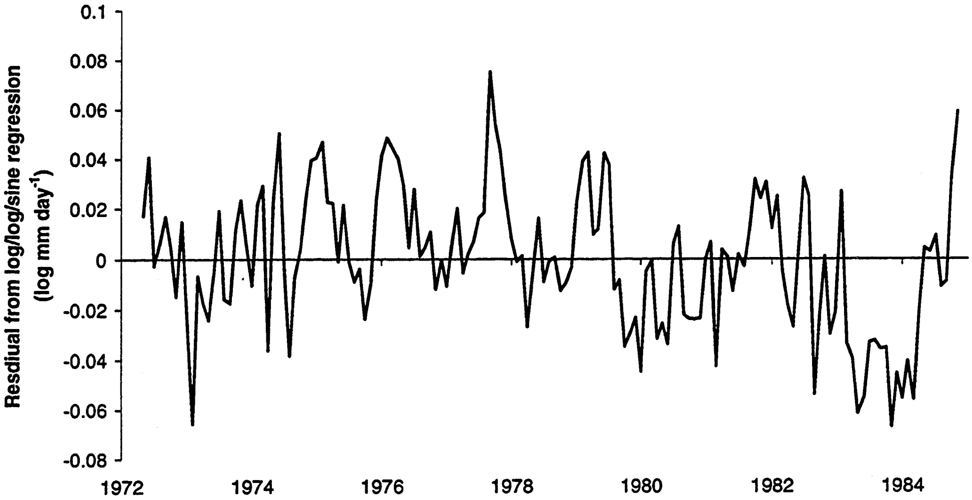

Figure 12: Time series of residuals from log/log/sine regression, showing no periodicity but remaining serial correlation.

confirmed by the correlogram in Figure 13 which shows statistical significant serial correlation up to a three month lag (solid line).

3.4.5 Adding an AR1 model

Serial correlation in a seasonally corrected time series can be removed by fitting to the residuals a stochastic time series model of the auto-regressive moving-average (ARMA) family (Salas, 1993). The simplest case is a lag-one auto-regressive (AR1) model, which, for residuals with zero mean can be written as:

$$\log \hat{y}_t - \log y_t = \phi(\log \hat{y}_{t-1} - \log y_{t-1}) + \varepsilon_t \tag{4}$$

where $\log \hat{y}_t - \log y_t$ is the residual from the log/log/sine model at time t, $\phi = 0.518$ is the auto-regression parameter which is estimated as the lag-one autocorrelation coefficient, and ε_t is a normally distributed random error term.

The AR1 component can be removed from the time series of residuals leaving just the 'disturbance', a_t (*sensu* Kuczera, 1983a):

$$\begin{aligned} a_t &= (\log \hat{y}_t - \log y_t) - \phi\,(\log \hat{y}_{t-1} - \log y_{t-1}) \\ &= (\log \hat{y}_t - \log y_t) - 0.518\,(\log \hat{y}_{t-1} - \log y_{t-1}) \end{aligned} \tag{5}$$

which is plotted as a time series in Figure 14, and as a correlogram in Figure 13 using a dashed line. The number of positive and negative runs and the

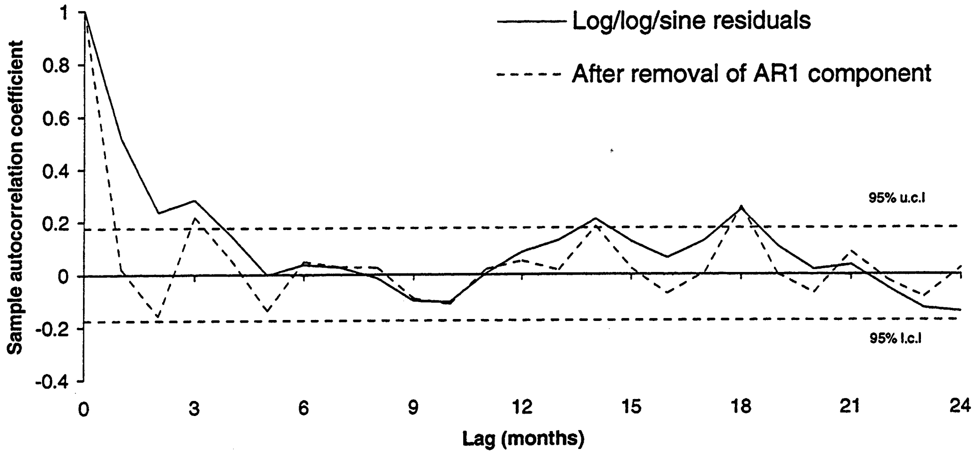

Figure 13: Correlogram of residuals from log/log/sine regression, showing no periodicity but significant serial correlation up to a three month lag. Also shown is the correlogram of the disturbances of the residuals after removal of the AR1 component.

apparent trend has been reduced. Additionally, all non-zero-lag autocorrelation coefficients now lie within or near the 95% confidence limits, implying that serial correlation has been removed.

The disturbance, a_t, is not a measure of the total deviation from pre-treatment conditions at month t. Rather, it is a measure of the component of the deviation which is specific to month t, any component 'inherited' from previous months having being subtracted out by the AR1 removal procedure. A single, statistically significant disturbance is indicates a statistically significant treatment effect, and a series of them indicate a persistent effect.

3.4.6 Check for normality

Having corrected for non-uniformity, heteroscedasticity, seasonality, and serial correlation, a final check was made to ensure that the remaining disturbances were normally distributed. This was done using a graphical Kolmogorov-Smirnov test (Barber, 1988) as shown in Figure 15. The cumulative distribution function (CDF) of the standardised disturbances is not significantly different from the CDF of a standard normal distribution confined within confidence limits indicated by the Kolmogorov-Smirnov test statistic. Thus the disturbances are approximately normally distributed.

3.4.7 Final residuals, prediction intervals, and moving averages

Because the disturbances have been shown to be appropriately distributed, 95% prediction intervals are able to be placed around the full time series of

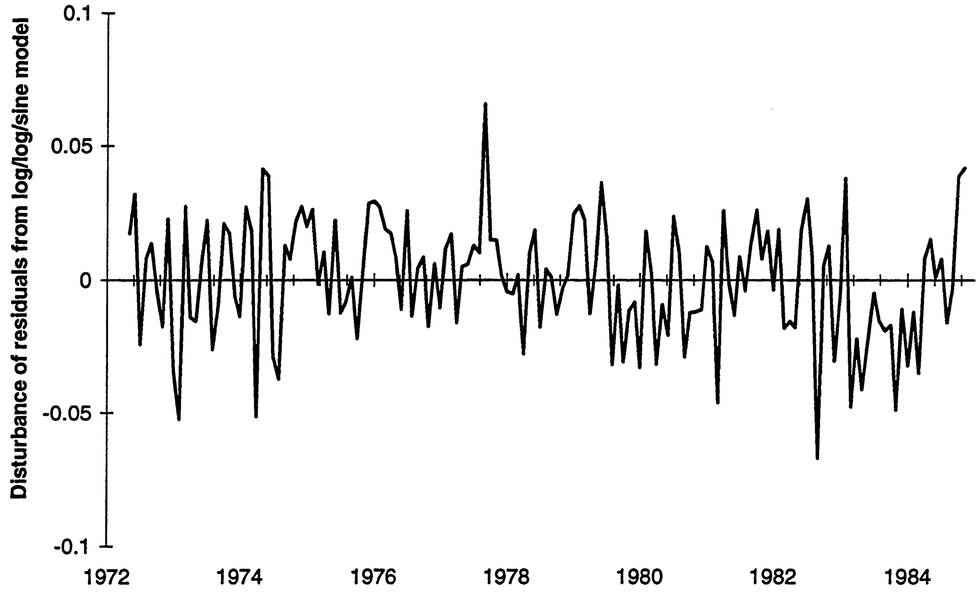

Figure 14: Pre-treatment time series of disturbances at Myrtle 2, i.e. residuals from log/log/sine regression after removal of the AR1 component.

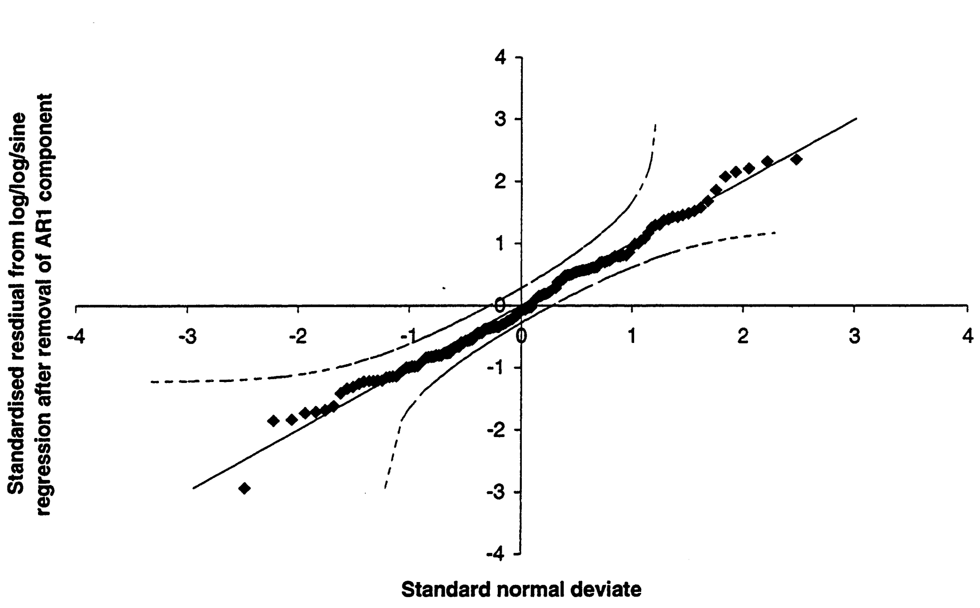

Figure 15: Graphical Kolmogorov-Smirnov test that the disturbances (residuals from the log/log/sine model after removal of the AR1 component) are approximately normally distributed.

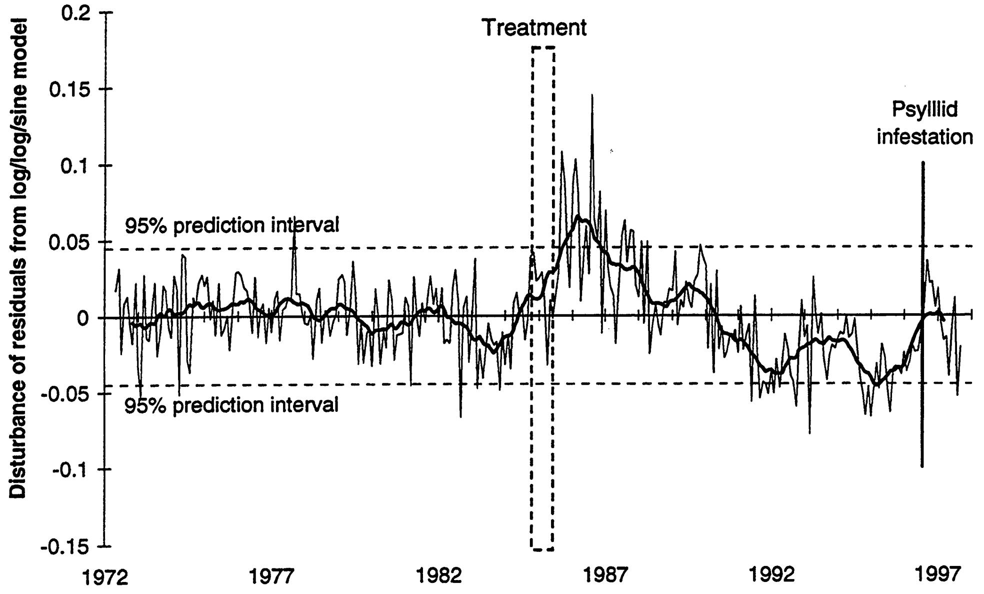

Figure 16: Full time series of disturbances of residuals from log/log/sine model at Myrtle 2 using Myrtle 1 as a control, including 95% prediction intervals.

residuals as shown in Figure 16. The disturbances as plotted are a measure of the effect of forest treatment on monthly streamflow at Myrtle 2. Zero disturbance means zero effect. More than 5% of disturbances outside the 95% prediction interval is a statistically significant deviation. In the pre-treatment period, significant deviation from zero occurs occasionally (about 5% of the time), and significant deviations occur more than 5% of the time in the post-treatment period. These results are discussed further below.

To facilitate better visualisation of trends, a 12 month moving average is included in Figure 16 and subsequent plots. This was calculated to be unbiased to the endpoints of the 12 month averaging window, after Chatfield (1989), as:

$$\bar{v}_{t,12month} = \frac{\frac{v_{t-6}}{2} + \sum_{i=-5}^{5} v_{t+i} + \frac{v_{t+6}}{2}}{12} \tag{6}$$

where v_t is the residual for month t, and $\bar{v}_{t,12month}$ is the 12 month moving average centred on month t.

The plot of disturbances with prediction intervals (Figure 16) established that statistically significant treatment effects occurred. However, to quantify the magnitude of these effects, we must return to the residuals from the log/log/sine model (not the disturbances), and re-linearise them (from the log domain to the linear domain):

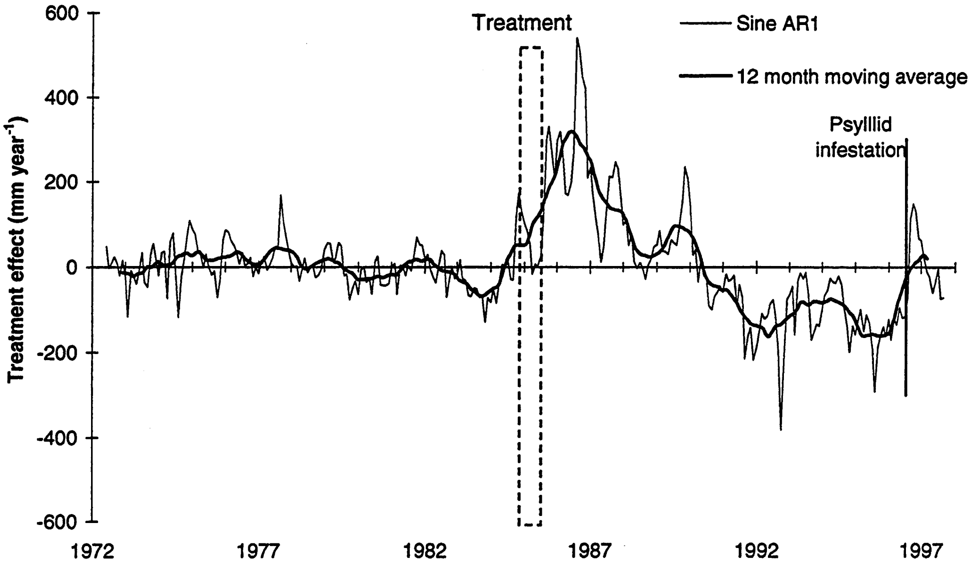

Figure 17: Treatment effects on monthly streamflow at Myrtle 2: re-linearised residuals from the log/log/sine model plotted in mm year^{-1}.

$$\text{linear residual}_t = y_t - 10^{\log \hat{y}_t} \tag{7}$$

After scaling the values in mm day^{-1} by the number of days in a year, the treatment effect could be expressed in mm year^{-1} as shown in Figure 17.

Further results from this analysis of the Myrtle group are discussed below in Section 3.5.

3.4.8 Summary of method

To summarise, the final method of assessing the effects of forestry on streamflow was to construct a regression of log flow in the treated catchment against log flow in the control catchment, including a sinusoid as an additional independent variable to remove seasonality. Auto-regression was removed from the residuals by fitting a lag one auto-regressive (AR1) model, to yield a time series of disturbances. These values were shown to be unbiased, stationary, uniform in x, normal in y, and independent, thus enabling 95% confidence limits to be placed around them, and an establishment of statistically significant post-treatment deviation to be made. Visualisation of trends was assisted by taking a special form of 12 month moving average. The magnitude of treatment effects was quantified by taking the residuals from the log/log/sine model before removal of the AR1 component, and re-linearising them.

This method was applied to all the treated subject catchments and the results

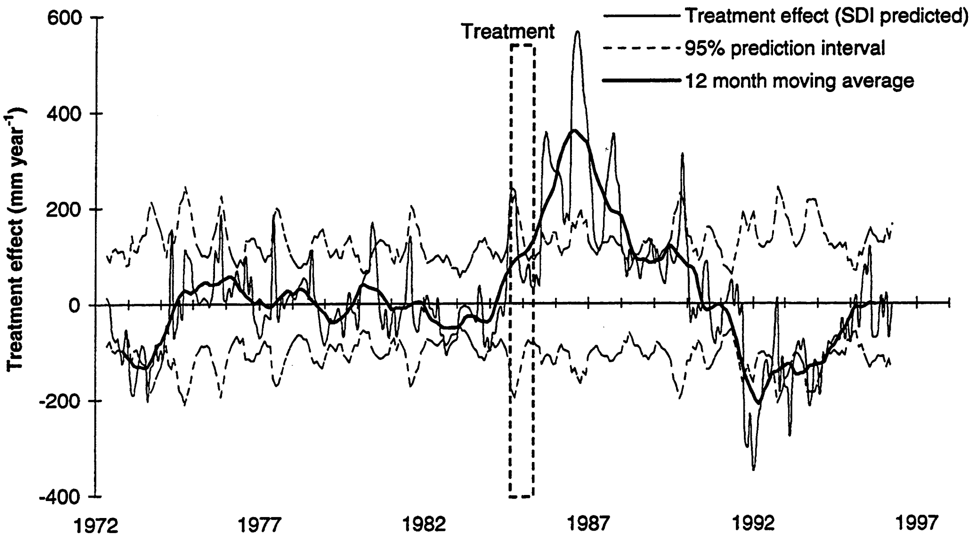

Figure 18: Time series of residuals from SDI modelling of Myrtle 2 monthly streamflow, including 95% confidence limits.

are discussed in Section 3.5.

3.4.9 Comparison with water balance modelling methods

As noted in the literature review above, an alternate method of determining the effects of forestry on streamflow is to use a simple water balance model to predict streamflow at the treated catchment. The model is calibrated on pre-treatment data and used to predict the post-treatment streamflow which would have occurred had treatment not been applied. The residuals are estimates of the treatment effect.

The SDI model is used operationally by Melbourne Water for this purpose. Results for Myrtle 2 can be used to qualitatively compare the SDI method with the method outlined above. Figure 18 shows the SDI residuals and associated 95% confidence limits. Qualitatively, the present method and the SDI method give similar results. The magnitude of the treatment effect is similar, there is a similar amount of noise in the raw residuals, and factors such as climatic variability appear to affect the moving averages to the same extent. On the basis of these results, there is no reason to choose the SDI method ahead of the present method. With only five parameters (four in the regression and one in the AR1 model), the present method is more parsimonious and a more clearly defined analytical tool than SDI. SDI has up to 12 parameters (Kuczera, 1988b) and casts the problem in terms of hydrological water balance, which is of only peripheral value here.

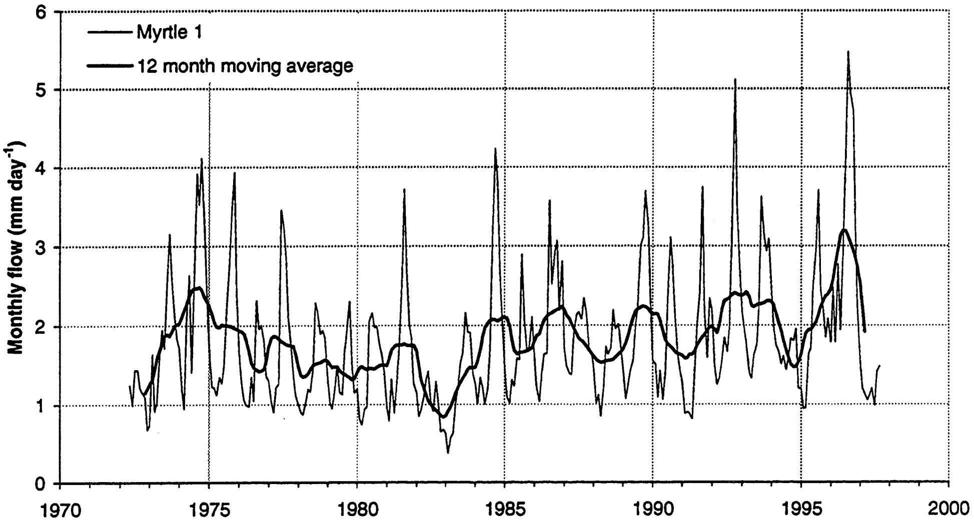

Figure 19: Streamflow at Myrtle 1, an old-growth control catchment, shown as a reference for climatic variability.

3.5 Results

3.5.1 Climate variability

Before discussing the effects of forestry treatment on water yield, a time series of flow from the Myrtle 1 catchment (old-growth control) is presented in Figure 19 to provide an indication of climatic variability. In the discussions below, this will be referred to in order to identify particularly wet and dry years in order that the coincidence of such years with events such as insect infestation may be identified.

3.5.2 Myrtle group

The Myrtle analysis, which was used to illustrate the analytical method, is discussed first. As a reminder, Myrtle 2 was 74% clearfelled during the 1984/5 summer, and Myrtle 1 was the control catchment.

In the post-treatment period, significant positive disturbances are consistently observed in Figure 16 for 2-3 years after treatment. These then decline until, at about 6 years after treatment, a four year period with a tendency for significant negative deviations occurs. The plot of linear residuals in Figure 17 shows that the effect of forest treatment (74% clearfelling, Ord, 1985, p. 1) at Myrtle 2 is for streamflow to rise to a peak about 2-3 years after treatment and then fall to a dip at about 10 years after treatment. The results also show that un-modelled variability in streamflow due to factors such as climate is large relative to the magnitude of treatment-induced change in streamflow. Smaller scale treatments may be difficult to characterise as having statistically significant impacts on streamflow.

The long term streamflow pattern predicted by the Kuczera curve leads us to expect that reduced streamflow will persist at Myrtle 2 for some decades beyond the plotted period of record. However, the plotted record ends with an apparent recovery to pre-treatment flows. This may be a real recovery, or be simply an artefact of climatic variability. It may also be associated with the 1996 Psyllid infestation shown in Figure 16. The expected result of such an infestation is reduced ET due to forest die-back, and consequently, increased streamflow. The 1996 infestation coincides with an increase in flow, supporting the idea that Psyllids have played a role. But it also coincides with the year of greatest streamflow in the Myrtle 1 record (Figure 19), so there is some uncertainty.

3.5.3 Monda group

Monda catchments 1, 2, and 3 were clearfelled and either seeded (Monda 2) or re-planted (Monda 1 and 3) at nominal densities of 2000, 5000, and 500 seedlings ha^{-1} respectively in the summer of 1977/8. Regeneration at Monda 2 was achieved by scattering seed at 3.2 kg ha^{-1}, which, based on seed viability tests, was expected to result in at least 5000 seedlings ha^{-1}, and probably closer to 10 000 (R. Benyon, CSIRO Forestry and Forest Products, pers. comm.). Monda 4 was intended to be the control, but was decommissioned due to sub-surface boundary delineation problems. Ettercon 3 replaced Monda 4 as the control catchment. The pre-treatment period was 76 months.

Individual disturbance plots for the three treated catchments of the Monda group are shown in Figure 20. It might be expected that because the pre-treatment forests of these catchments were 1939 regrowth with low water yield, that the initial effects of clearing and regeneration would be greater than observed at the Myrtle group. However, the residuals in the post-treatment period do not stray outside the 95% prediction intervals as often as those for the Myrtle group. An alternative suggestion is posed that because soils beneath the high water use 1939 regrowth forest were drier than those of old-growth forest, they had a greater capacity to absorb excess precipitation, thereby dampening the expected yield increase.

All three catchments experienced an increase in flow in the 2-3 year period following treatment, but none experienced a reduction in flow at any time following treatment. This may be explained by the fact that the 33-39 year old pre-treatment forest at Monda was probably already near minimum water yield, according to the Kuczera curve.

The moving average residuals from the three catchments are overlaid, back-transformed, and scaled to mm year^{-1} in Figure 21. There is a distinct difference between the catchments in the degree to which flow increased

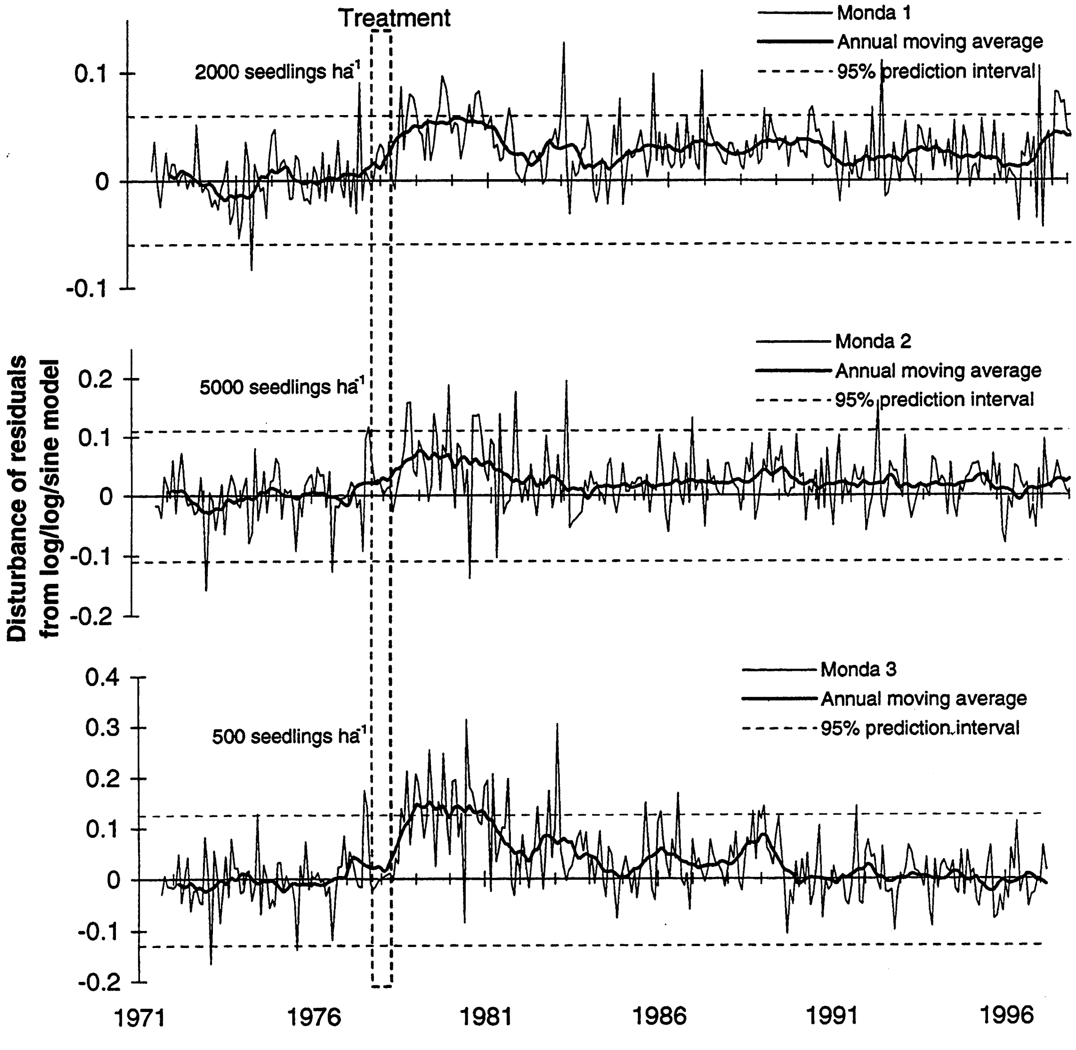

Figure 20: Disturbance of residuals from log/log/sine model of monthly streamflow at Monda 1, 2, and 3 using Ettercon 3 as a control.

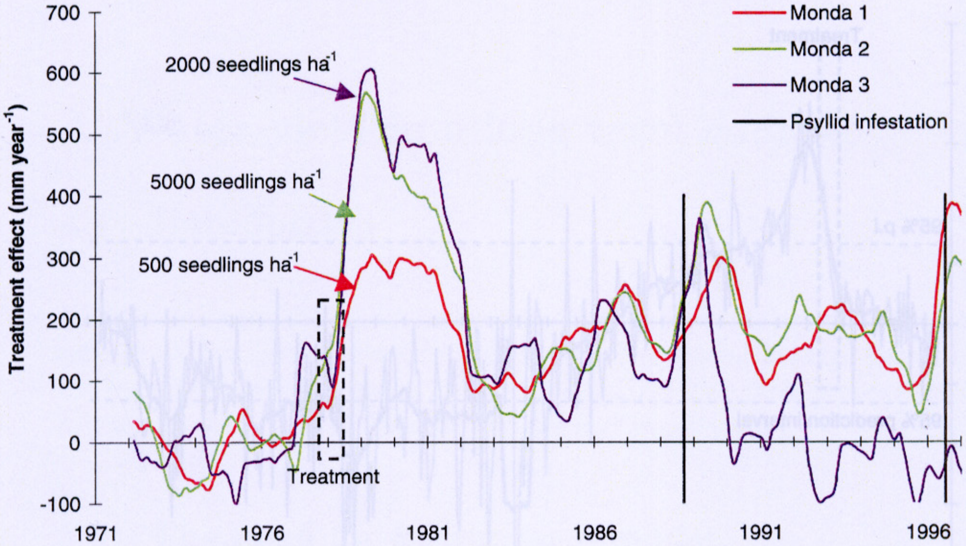

Figure 21: Treatment effects on monthly streamflow overlaid for Monda 1, 2, and 3 (annual moving average of re-linearised residuals from log/log/sine model).

immediately following treatment. This difference does not correlate with seedling density, nor would this be expected. The difference can not be explained by differences in the treated fractions of the catchments, as these are approximately equal (see Table 1). Of the catchment parameters listed by Moran and O'Shaughnessy (1977, p. 54), only the maximum vertical relief of the catchments correlates (positively) with the increase in yield.

As shown in Figure 21, two Psyllid infestations occurred at Monda: in 1988 and 1996. Both were accompanied by increases in flow, Monda 3 more so in 1988, and Monda 1 and Monda 2 more so in 1996. Unlike the 1996 infestation, the 1988 infestation was *not* accompanied by a wet year (see Figure 19), thus implicating the Psyllids more strongly. Note also that the control catchment for this analysis, Ettercon 3, was itself infested by Psyllids in 1988, although to not as great an extent as the Monda group (J. Snodgrass, pers. comm.).

The possibility is raised that the reason that reduced flows never occurred in the Monda group was because at the time when flow reduction would be expected to occur (the mid to late 1980s), Psyllid infestation offset this by curtailing ET and increasing runoff. If a secondary regeneration cycle then took place, this may have been offset by the second infestation, 8 years after the first. Whilst the forests have ultimately regenerated, they have *not* done so in a unified, vigorous fashion with a peak in growth 5-15 years after treatment, as may be expected for the Mountain Ash species based on the background LAI curves presented in the introduction.

The intention of the Monda experiment was to test the effect of different seedling densities on forest regeneration, and hence on water yield. However,

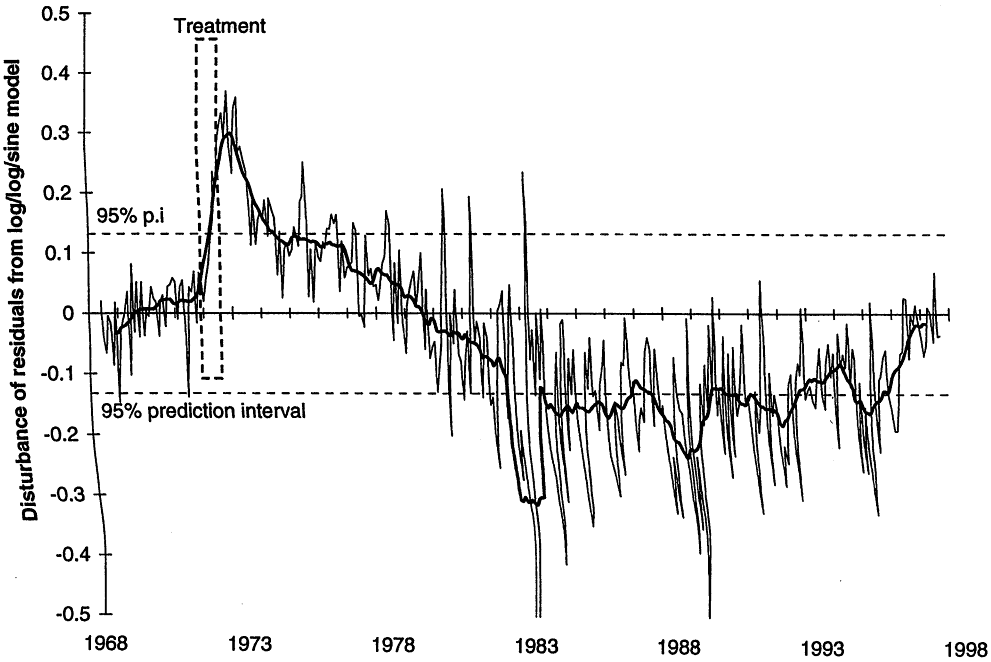

Figure 22: Disturbance of residuals from log/log/sine model of monthly streamflow at Picaninny using Slip as a control.

extraneous influences, seemingly connected with Psyllid infestations, appear to have outweighed the influence of the different seedling densities. However, the experiment has provided valuable information on the extent to which extraneous influences may occur, and suggests that insect infestation is a significant agent of changing water yield patterns in these forests.

3.5.4 Coranderrk group

The Picaninny catchment of the Coranderrk group was 78% clearfelled in the summer of 1971/2, and the Slip catchment was the control. The pretreatment period was 42 months. Thus, if a method based on annual data had been used, only three data points would have been available.

The streamflow history for the Picaninny catchment, as hown in Figures 22 and 23, conforms best to the classic stand age/water yield relationship developed by Langford and Kuczera. It shows a distinct peak in flow almost immediately following treatment, followed by a steady decline over the next 10 years to a low point which persists for another ten years when a recovery is apparent, but not certain.

The decline in flow is slower than at Myrtle 2, which may be due to problems with forest regeneration at Picaninny which lasted until about 1977 (as noted earlier, see also O'Shuaghnessy, 1980).

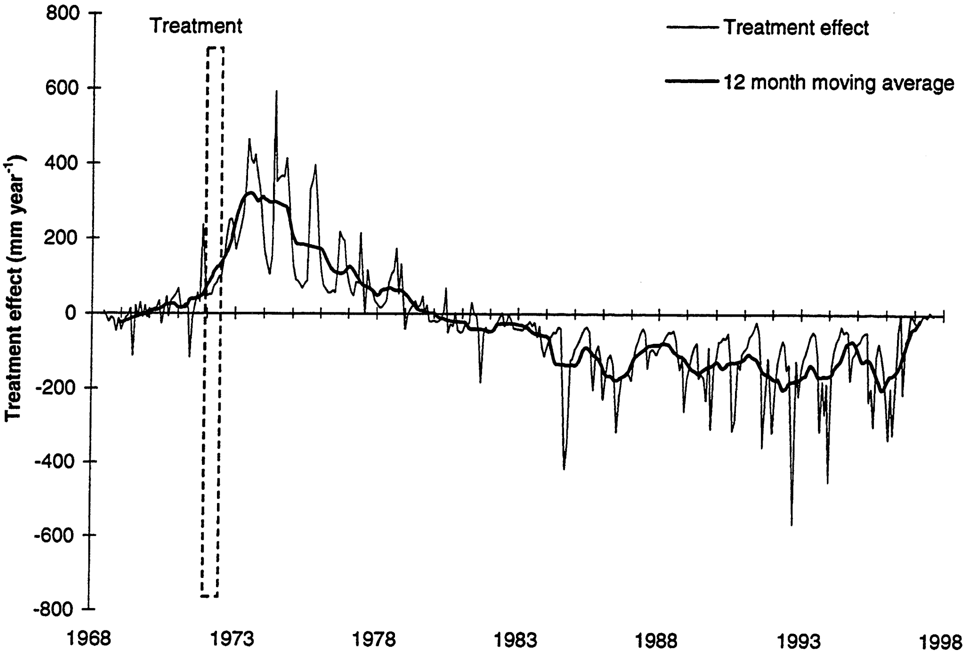

Figure 23: Treatment effects on monthly streamflow at Picaninny (re-linearised residuals from log/log/sine model).

4. Water yield in a long term context

4.1 Introduction

This section describes the construction of a simple water balance model which uses precipitation and flow data as input. The model enables data from all the experimental catchments to be combined in a long term context, resulting in long term curves for forest water use and water yield.

4.2 The need for a long term model

Ideally, the residual plots for all of the experimental catchments could be overlaid on the same chart so that they may be compared. However, this would be misleading because:

- the treated fraction of each catchment differs,
- the mean pre-treatment water yield of each catchment differs from the others,
- and the pre-treatment forests for each catchment differ in age.

It is this last factor which is the most confounding. The residual plot for each catchment represents the effect of treatment *relative to the natural development of the pre-treatment forests.* Some pre-treatment forests were 1939 regrowth, and others were old-growth forests. In no cases could the pre-treatment conditions be considered stationary.

If a stationary predictor of pre-treatment flow were available, then the residuals from the resulting predictions could be compared between any catchments regardless of pre-treatment forest age.

To this end, a simple water balance model was constructed, employing precipitation as a stationary predictor of streamflow. The model has a single store, can be calibrated by least squares regression, and is described as follows.

4.3 A simple, single-store water balance model

The simplest possible catchment water balance model is:

$$Q_t = P_t - E_t \tag{8}$$

where Q_t is catchment streamflow at time step t, P_t is catchment precipitation, and E_t is catchment evapotranspiration. At time steps greater than a year or two, such a model is suitable (provided there are no deep drainage losses). However, in many situations such as the present, catchment storage effects retard precipitation and cause streamflow to be a function not only of current precipitation, but also of stored water resulting from previous precipitation. The present study area exhibits deep, high storage soils and since a monthly time step is desired, storage effects are likely to be pronounced. A simple storage model was thus formed:

$$S_t = S_{t-1} + P_t - Q_t - E_t \tag{9}$$

$$Q_t = f(S_t) \tag{10}$$

where S_t is the amount of stored water at time step t, and f is the discharge/storage function of that store. It is common in baseflow recession analysis studies to assume linear catchment storage such that $f(S) = aS$, where a is a baseflow recession constant (e.g. Nathan and McMahon, 1990). This leads to exponential baseflow recession with respect to time. However, Watson et al. (1996) found that Maroondah experimental catchments are better modelled with exponential discharge/storage functions, as inferred by their first order hyperbolic baseflow recessions. Thus an exponential form for f was chosen:

$$Q_t = f(S_t) = a\ \exp(bS) \tag{11}$$

where a and b are constants. This can be inverted as:

$$S_t = \frac{1}{b}\ \ln(\frac{Q_t}{a}) \tag{12}$$

which can be substituted into Equation 9 giving:

$$\ln(\frac{Q_t}{a}) = \ln(\frac{Q_{t-1}}{a}) + bP_t - bQ_t - bE_t \tag{13}$$

$$\ln(\frac{Q_t}{Q_{t-1}}) = bP_t - bQ_t - bE_t \tag{14}$$

which can be re-written as a linear regression:

$$\ln(\frac{Q_t}{Q_{t-1}}) = b(P_t - Q_t) - b\bar{E} + \varepsilon_t \tag{15}$$

$$\varepsilon_t = -b(E_t - \bar{E}) \tag{16}$$

where $\ln(\frac{Q_t}{Q_{t-1}})$ is the independent term, $P_t - Q_t$ is the dependent term, and:

$$\begin{aligned} \beta &= b \qquad (17) \\ \alpha &= -b\bar{E} \qquad (18) \end{aligned}$$

are regression coefficients to be estimated, and ε_t is the error term in the regression.

Once α and β have been estimated, the mean evapotranspiration, $\bar{E}$, can be calculated as:

$$\bar{E} = \frac{\alpha}{-\beta} \tag{19}$$

giving the estimate of evapotranspiration at time t, E_t, as:

$$E_t = \frac{\varepsilon}{-\beta} + \bar{E} = \frac{\varepsilon + \alpha}{-\beta} \tag{20}$$

The error term, ε is unbiased in the mean by definition. But it is non-stationary because it reflects long term changes in evapotranspiration. This means that the distribution of ε is uncertain and, hence, confidence limits cannot be placed around estimates of E_t. Similarly, the correlation coefficient associated with the regression is meaningless because the same term, Q_t, appears on both sides of the regression. These problems limit *but do not preclude* the use of estimates of E_t.

The outcome is then a simple, single storage water balance model, re-cast as a linear regression model, which provides monthly estimates of evapotranspiration given precipitation and streamflow data.

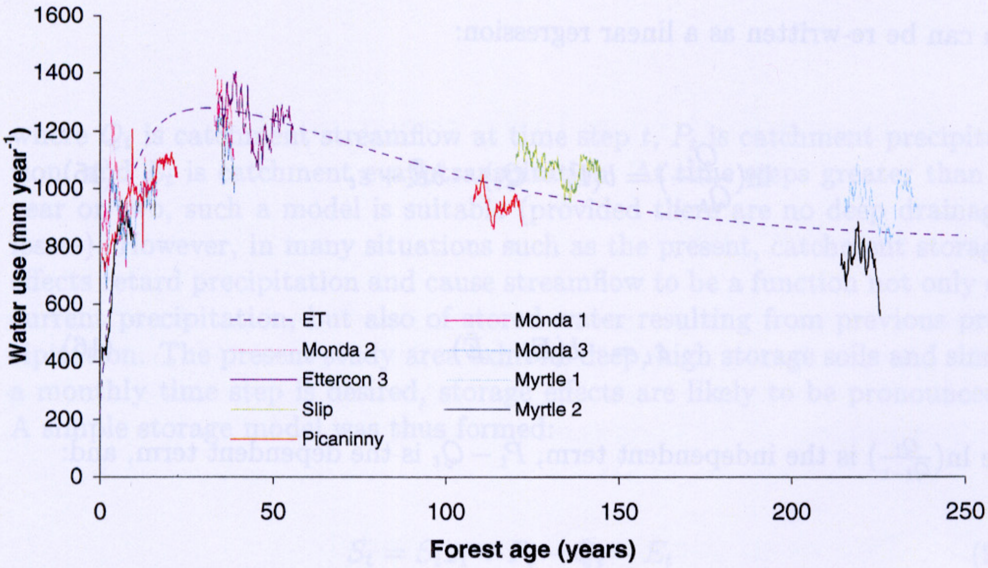

Figure 24: Changes in total forest evapotranspiration with forest age estimated using a simple water balance model calibrated by least squares linear regression. A three year moving average is plotted.

4.4 Application

The model was applied to monthly streamflow and precipitation data for each of the experimental catchments. The precipitation data were aggregated from the daily record at the Lower Coranderrk meteorological station, and scaled according to the average catchment mean monthly precipitation index (MMPI) values for each catchment described by Watson (1998). The resulting evapotranspiration term, E_t, is shown plotted against forest age in Figure 24 after smoothing using a 3 year moving average. A trend line was fitted by eye to the data as discussed below. An enlargement for young ages is given in Figure 25. Data for Monda 4 is not shown due to its unreliability. The data are scaled to represent units of millimetres per year.

Significant climatic noise is evident, even after smoothing by 3 year moving average. But within this, a long term ET trend is evident. For the oldest forests, it is possible that the level of noise is such the the trend is not statistically significant. An error analysis was not undertaken.

At age zero, ET is at its lowest, with Myrtle 2 having the lowest value. *Note that no account was taken of the fraction of the catchment which was logged, so the data for young aged forests as shown is diluted by the presence of some older aged forest within each catchment.* A similar exception arises for the old-growth control catchment, Myrtle 1, which is 'contaminated' by 13% regrowth forest (Ronan and Duncan, 1980, p. 83). For all catchments, ET rapidly rises to a peak, which apparently occurs somewhere between 20 to 40 years of age, although the data have not yet progressed this far. From

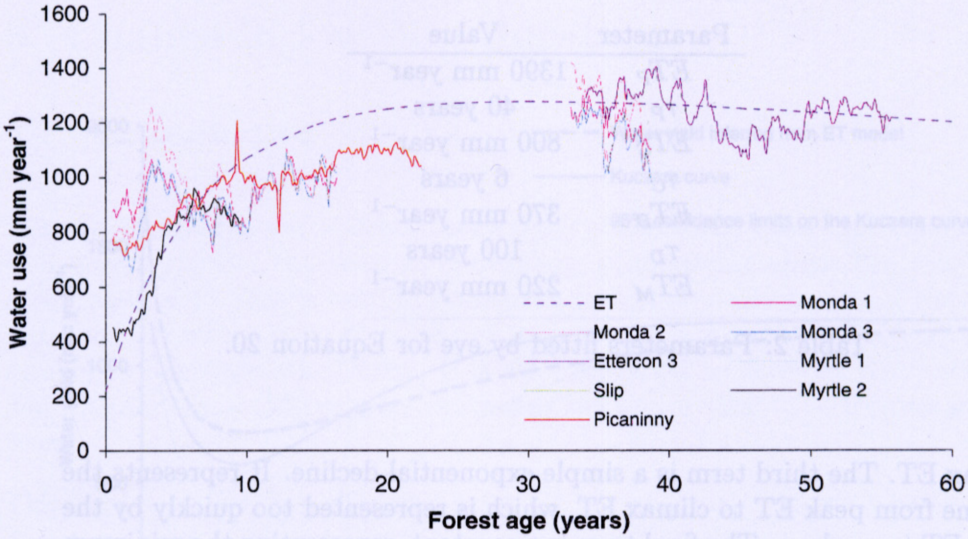

Figure 25: As for Figure 24 showing the first 60 years only.

about 40 years of age, ET gradually declines and continues to do so beyond 150 years of age.

4.5 A general forest evapotranspiration curve

A curve was fitted by eye to the ET estimates. It is of similar mathematical form to the curve used for total leaf area index (LAI) versus forest age by Watson (1998):

$$\begin{aligned} ET = \; & (ET_P - ET_C - ET_D) \quad \frac{e}{\tau_P} \, AGE \, e^{\left(\frac{-AGE}{\tau_P}\right)} \\ + \; & (ET_C + ET_D - ET_M) \left(\frac{2}{1 + e^{\left(\frac{-AGE}{\tau_C}\right)}} - 1 \right) \\ + \; & ET_D \quad \left(e^{\left(\frac{-AGE}{\tau_D}\right)} - 1 \right) \\ + \; & ET_M \end{aligned} \qquad (21)$$

with parameters as given in Table 2.

The curve has four terms and was designed to provide a flexible, controllable means of interpolating long term pattens of variables such as LAI, water yield, and ET. The first term starts at zero, rises rapidly to a peak, and declines more gradually back to zero. It represents the peak in estimated ET. The second term is one half of a sigmoid curve (Zurada, 1992) which starts at zero, rises, and steadies at a constant value. It represents the long term,

Parameter	Value
ET_P	1390 mm year^{-1}
τ_P	40 years
ET_C	800 mm year^{-1}
τ_C	6 years
ET_D	370 mm year^{-1}
τ_D	100 years
ET_M	220 mm year^{-1}

Table 2: Parameters fitted by eye for Equation 20.

climax ET. The third term is a simple exponential decline. It represents the decline from peak ET to climax ET, which is represented too quickly by the peak ET term alone. The final term is a constant, representing the minimum ET. The size of peak, climax, decline, and minimum can be easily changed by changing the *ET* constants. The time to peak, climax, and decline can also be changed easily using the τ constants.

4.6 A general forest water yield curve

The ET curve can be inverted to estimate changes in water yield versus age in the same manner as the Kuczera curve. In the following calculations, an annual precipitation of 1995 mm was assumed. This value is 800 mm plus 1195 mm, where 800 mm is the long term value of the ET curve fitted above, and 1195 mm is the regional average old-growth water yield estimated by Kuczera (1985, p. 149). Water yield may then be estimated as precipitation minus ET giving the curve shown in Figure 26.

Note that this new water yield curve inherits the limitation of the ET curve above, in that no account was taken of the catchments' treated fractions. The estimated relation between water yield and age is therefore biased to this effect. Further, the expected nature of this bias is uncertain, given that the un-treated fraction of the catchments is usually dominated not by Mountain Ash, but by rainforest species whose water yield dynamics are not well understood.

The new water yield curve is *not posed as a replacement or improvement to the Kuczera curve.* Rather, it was produced to show that the data from the experimental catchments can be synthesised in a single equation which matches the general form of our existing understanding of regional long term water yield patterns. It was fitted subjectively, it cannot as yet be described statistically, it is possibly applicable only at the scale of small experimental catchments, and it remains biased by the differing treated fractions of the catchments in question.

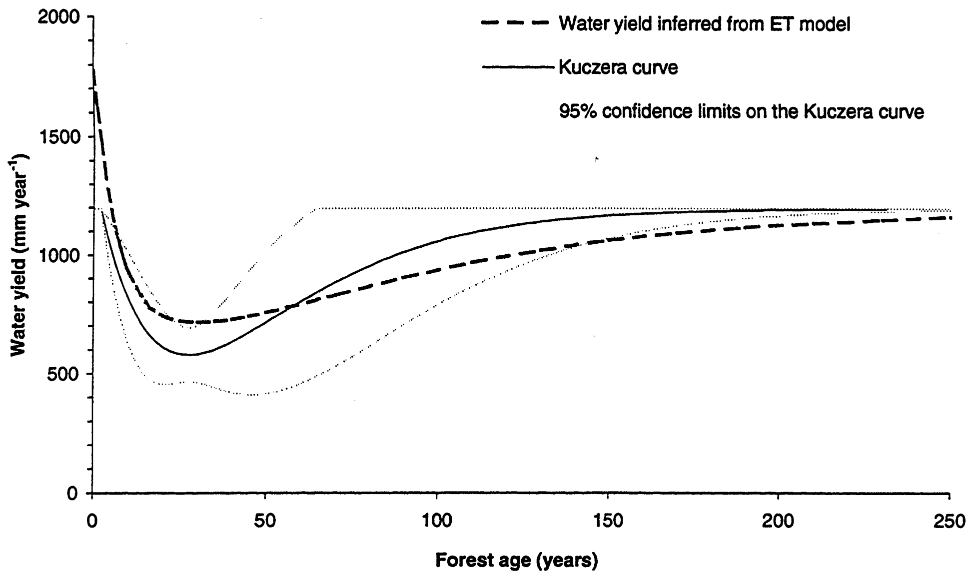

Figure 26: Water yield curves estimated by the water balance model, and by Kuczera's approach.

The similarities with the Kuczera curve are, however, encouraging. Both curves predict a marked decline in water yield to about half the long term value, reaching a minimum about 20 to 40 years after forest regeneration. Both curves then predict a gradual return to long term values over the following 100 to 150 years. That this general pattern can be observed by piecing together observations from a number of small experimental catchments distributed throughout a range of Mountain Ash forests is an important confirmation and extension of the observations of Langford (1974, 1976) and Kuczera (1985, 1987).

There are some key differences too. The present curve predicts a sharp increase in yield above long term values in the first 5 years and then declines, whereas the Kuczera curve remains at the long term value for two years before declining. This *is* considered to be an improvement to the Kuczera model, owing to the more detailed temporal scale of the present analysis. The amplitudes of the dips in yield differ, but this is not considered significant given that the present curve is 'diluted' by its failure to take account of catchments being cleared by less than 100 percent. Of relevance to the planning of long term cycles of timber harvesting is the time to recovery, which is longer according to the present curve. Again, however, this comparison should not be interpreted too strongly given the differences in scale and method, and the uncertainty implied by variation about the fitted line in Figure 24.

5. Change in low flow duration

5.1 Introduction

The previous sections established that a reduction in mean water yield results from forestry treatments such as clearfelling, commencing about five years after treatment. This is useful information for considerations of long term water supply where large storages are used to regulate supply. But where smaller storages are relied upon, it is also important to consider low flows and whether or not they experience more or less severe reductions than mean flows.

This section uses a flow duration curve (FDC) analysis to assess how low flow occurrence may have changed as a function of catchment treatment.

5.2 Method

For each subject catchment, an FDC was calculated for pre-treatment flows. Then, to assess the temporal dynamics of various flows, the post-treatment data were divided into five year blocks and an FDC was calculated for each.

5.3 Results

Figure 27 shows the results for all catchments.

The left column of charts shows the three catchments of the Monda group and their control, Ettercon 3. The various curves for Ettercon 3 differ considerably, indicating that climatic variability is sufficient to produce entirely different FDCs for each five year block. Thus, variability in the control catchment must be taken into account when assessing the FDCs of the treated catchments.

Looking at the curves for each of the Monda catchments, the post-treatment curves are always higher than the pre-treatment curves, more so than at Ettercon 3. This reflects the increase in mean flow at Monda. However, the post-treatment curves do not vary in slope from the pre-treatment curves, indicating that all flows increased in unison and that separate patterns were not evident for high, median, or low flows. A possible exception is the increased frequency of low flows relative to the mean in the first five years. However, this pattern was also observed at Ettercon 3 and reflects the severe 1982/3 drought that occurred in this period rather than any effect of treatment. A similar pattern was reported by Jayasuriya (1994, p. 105) for the Black Spur group, also spanning the 1982/3 drought.

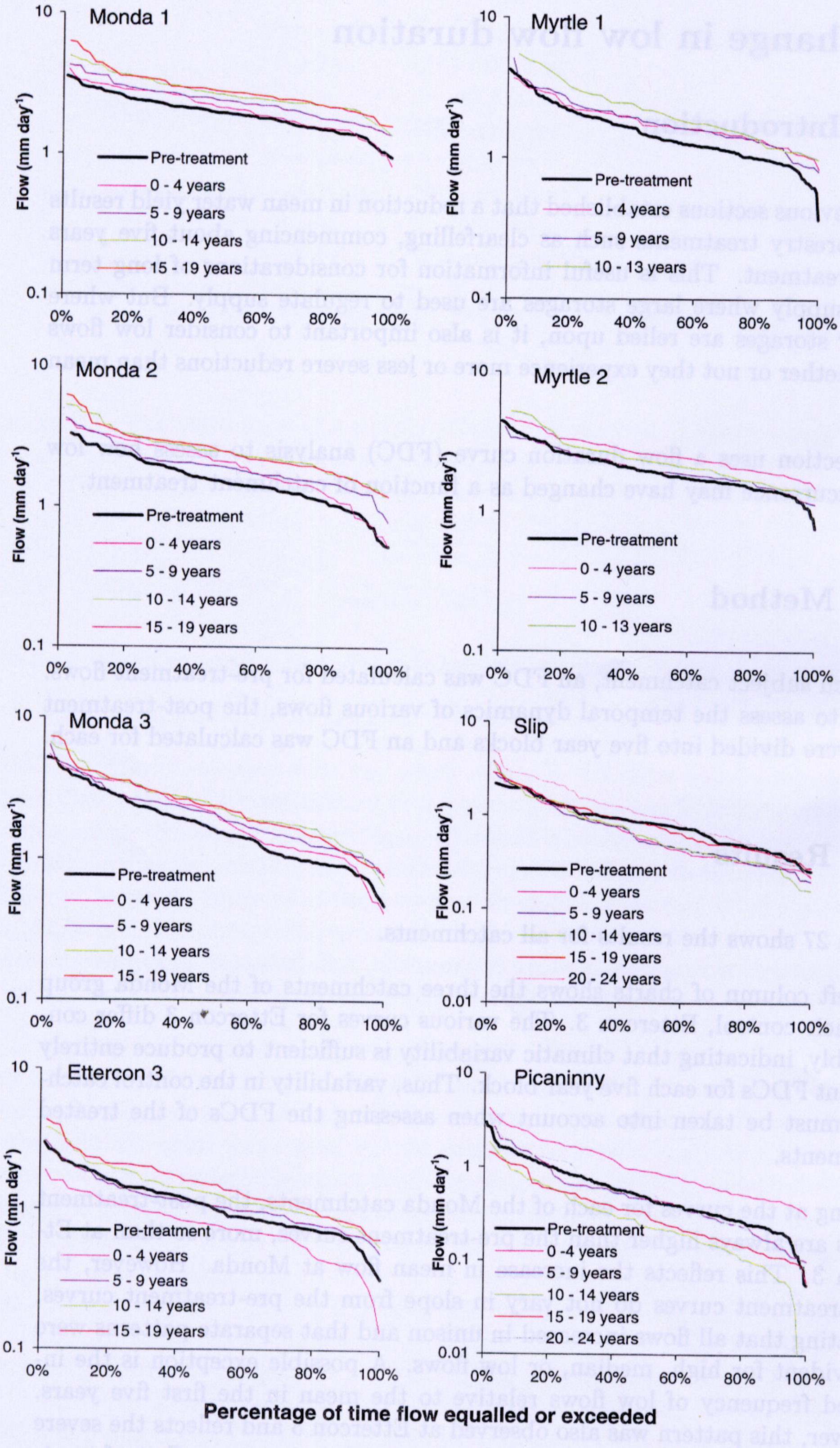

Figure 27: Flow duration curves for each of the treated catchments. In each case, curves are given for pre-treatment streamflow as a whole, and for post-treatment streamflow in 5 year blocks.

The right column of charts in Figure 27 contains the curves for Myrtle 2 and its control, Myrtle 1, as well as Picaninny, and its control, Slip.

The Myrtle group exhibit similar behaviour to the Monda group in that overall shifts are observed in the control as well as the treated catchment, but that the slope of the FDCs does not change greatly over time. Thus, there are no changes in low flows relative to mean flows at Myrtle either.

The Coranderrk catchments, Picaninny and Slip, do not follow the same pattern as the Myrtle and Monda groups. The FDCs for the control catchment, Slip, exhibit differences in slope as well as mean location, indicating that climatic variability in this drier part of the study area has the potential to change the magnitude of particular flows relative to changes in the mean flow. The treated catchment, Picaninny, experiences significant changes in mean flow, and also some noticeable changes in the shape of the FDC at the lower extreme. The curve for 10-14 years post-treatment is steepest of all and has a steeply lower tail. This corresponds to the period spanning the 1982/3 drought and occurred at a time when ET demand would have been very high. It indicates that whilst mean flow at Picaninny dropped in this period, and it also dropped relative to Slip, the lower flows were worst affected, particularly the lowest flows. In one month, flow at Picaninny ceased.

5.4 Conclusion

It can be concluded that, for the typical wet catchment of the study area, all percentile flows respond to climatically and ecologically induced changes in unison with mean flows. However, in the drier parts of the study area, such as at Picaninny, changes in flow brought about by either climate or forestry are accentuated for lower percentile flows, particularly for the lowest decile. If a mean reduction in flow occurs, low flows are most sensitive to this. Note that, relative to many Australian forests, Picaninny is not dry at all, having a mean annual rainfall of 1180 mm. It stands to reason then, that forests drier than this would be expected to exhibit significant changes in low flow occurrence following disturbance.

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6. Soil moisture

6.1 Introduction

This section summarises the soil moisture data collected as a part of the Maroondah experimental programme, and selects for analysis that data which can be used in a longer term examination of the effects of forest treatment. Data from Picaninny and Slip are useful to this end, and are analysed to determine the effect of treatment on soil moisture, and how this relates to concomitant changes in water yield.

6.2 Soil moisture data

As explained below, the analysis of soil moisture data is limited to the Picaninny and Slip catchments, but the data set for all the experimental catchments is described for completeness.

From 1974 to 1984, an extensive soil moisture measurement programme was undertaken by Melbourne Water. Between 6 and 16 neutron moisture meter (NMM) boreholes per catchment were sited in eight of the experimental catchments. Within each borehole, measurements were taken at up to 17 depths from 0.3 to 5.2 metres. Typically, it took one day to measure all the holes in a given catchment, and each catchment was measured at fortnightly intervals.

The NMM operates with a neutron source and an adjacent neutron counter. Over a fixed period the number of neutrons recorded by the counter will increase if there is moisture nearby which scatters the neutrons. As described by Howard and O'Shaughnessy (1971, p. 99), measurements at each hole commenced with a number of one minute calibration counts with the NMM in a calibration shield. Then, at each depth, two 30 second counts were taken. Finally, a number of further one minute calibration counts were taken to complete the procedure.

The data from the Black Spur group were analysed by Langford and O'Shaughnessy (1979b) who found that soil moisture drying rates over summer could be explained by stem density, initial moisture content, and elevation. Later at Black Spur, Jayasuriya and Creaner (1994) observed increases in soil moisture resulting from reduced evapotranspiration in thinned and patch cut catchments, particularly in summer.

Melbourne Water archives the soil moisture data in the original computer card-reader format in which it was collected. A conversion process was undertaken before it could be used in the present work. The raw data comprise a six megabyte file of borehole measurements in an arbitrary order.

A converter was programmed to read this file and produce a Microsoft Excel spreadsheet with 7283 rows (one for each borehole measurement) and 70 columns (one for each field on the borehole measurement card. The converter detected a few hundred typographical errors in the raw data, the most common of which were missing digits in the five digit field used to record neutron counts. These were treated by either: deleting the field if other duplicates remained; or supplying '5' as the missing digit if this would not influence the resulting count by more than one percent. Other errors, such as erroneous dates, were corrected by inferring values for the affected fields from neighbouring records.

Figure 28 summarises the extent of the soil moisture record for each of the eight catchments. Numerous gaps exist within these records. Note that the Myrtle 2 measurements are divided in to general measurements at Myrtle 2, and those made at the permanent forest inventory plots within Myrtle 2. Here, we describe a preliminary analysis of the data set, using heavily averaged measurements, described as follows.

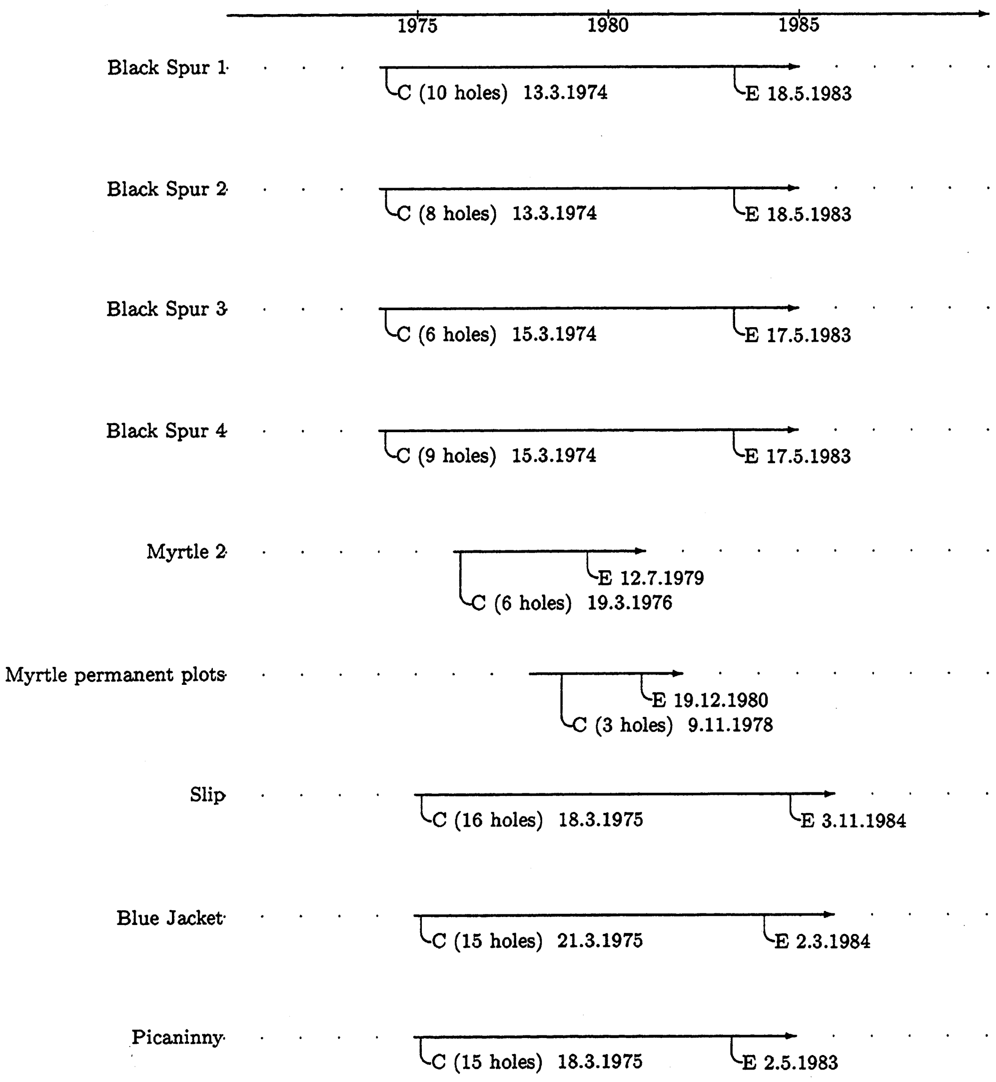

Figure 28: Time lines for soil moisture data at each of the experimental catchments.
C = Commencement of record; E = End of record.

Soil moisture content was calculated using the site-specific calibration published by Duncan and Heeps (1980, p. 133):

$$M = \frac{1}{1000}\left(589.3 \times 2 \times \frac{C_{soil}}{C_{shield}} + 193.1\right) \tag{22}$$

where M is the volumetric soil moisture content in metres of water per metre of soil; C_{soil} is the average of the two 30 second, in-soil counts taken at the depth in question; and C_{shield} is the average of the average pre-measurement and average post-measurement one minute, in-shield calibration counts. The same calibration was used for all catchments, which may be a source of error due to variation in the relationship between soil moisture and neutron counts associated with soil variation.

An average moisture content was calculated for each borehole measurement. This will be biased away from depths where, for some reason, measurements were not made at a given borehole.

The borehole average moisture content data were organised into a table indexed by the 624 unique measurement dates as rows, and the 85 unique boreholes as columns. Borehole averages were further averaged as catchment averages. This resulted in a similar, smaller table indexed by the eight catchments. Finally, some temporal aggregation into fortnightly data was performed yielding a table indexed by the 283 fortnights from 1974 to 1985 as rows, and the eight catchments as columns. In this way, one to one comparisons could be made between data from two separate catchments so long as they pertained to the same fortnight.

To summarise, the individual moisture content values used in the following analysis are fortnight averages of catchment averages. These were derived from borehole averages of moisture content measurements at different depths based on repeat neutron count averages. Hence, a very large data base has been reduced to a small one, thus masking a great deal of spatial and temporal variability in soil moisture patterns in the catchments.

6.3 Analysis

Only the Picaninny and Slip data were used. The Black Spur and Blue Jacket data apply to catchments outside the scope of this report. The Myrtle 2 data apply to the pre-treatment period for that catchment and therefore are of no use in examining the effects of treatment.

The Picaninny and Slip data are shown in Figure 29. Seasonal variations in moisture content are almost 20%. There is a trend toward drier values in both catchments later in the period, which reflects a decline in precipitation

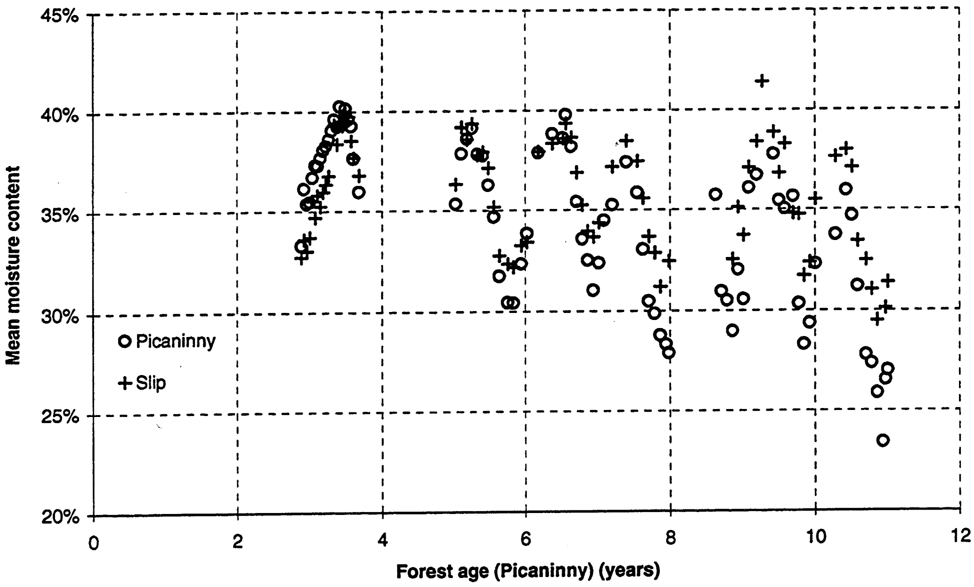

Figure 29: Time series of average soil moisture at Picaninny (treated) and Slip (control).

during this period, culminating in the extreme drought conditions of 1982 and 1983 (ages 10 and 11).

The analysis of the Picaninny and Slip data is simple. For all fortnights where data were available for both catchments, the difference in percentage moisture content between the two catchments was calculated. This is plotted against forest age at Picaninny (the treated catchment) in Figure 30. Forest in the control catchment, Slip, was aged approximately 124-134 years old during the period shown.

We assume that the borehole networks in Picaninny and Slip are representative of catchment moisture conditions to the same degree, that if bias exists, then the two are biased to the same degree. Indeed, the networks were designed with this intent (Howard and O'Shaughnessy, 1971, p. 98).

The data commence three years after treatment, at which time Figure 30 shows that the soils at Picaninny were slightly wetter than those at Slip. Over the following ten years, Picaninny dried by over 5% moisture content relative to Slip. At the end of the record, Picaninny remained drier than Slip.

6.4 Relation of soil moisture to overall water balance

Pre-treatment soil moisture data at not available at Coranderrk. However, it is reasonable to assume that values at Picaninny in the pre-treatment pe-

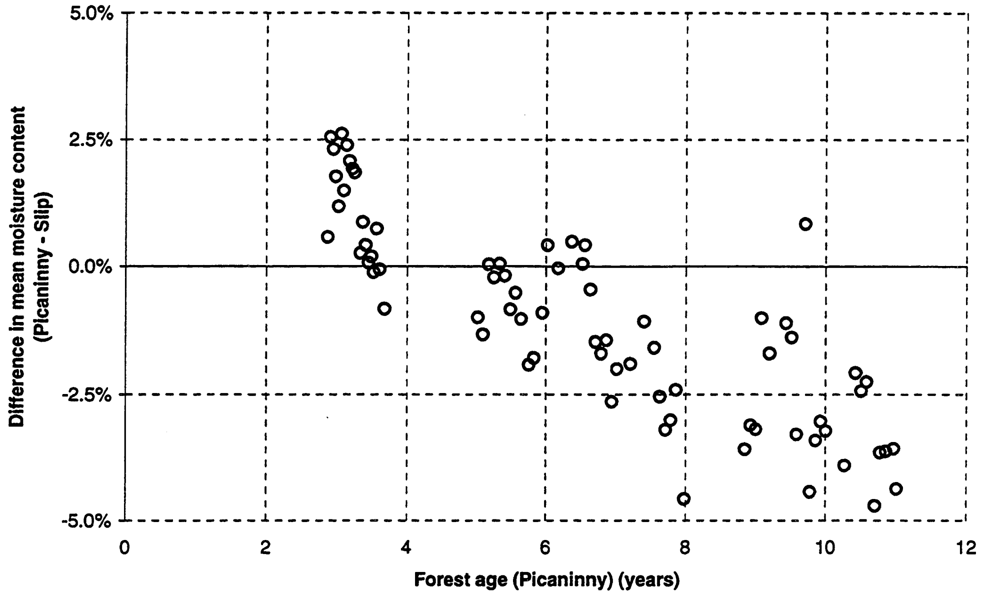

Figure 30: Effect of forestry on soil moisture over time: represented as the difference between a treated catchment (Picaninny) and a control (Slip).

riod were slightly lower than those at Slip because of the lower precipitation experienced over the Picaninny catchment (catchment precipitation is 15% lower at Picaninny according to the analysis performed by Watson, 1998). It follows that in the long term, we could expect the difference in soil moisture between Picaninny and Slip to be slightly negative. In Figure 31, the soil moisture difference data are plotted alongside the new long term water yield curve from Figure 26, with zero soil moisture difference aligned on the y-axis with the long term water yield value (1100mm). Remembering that the expected long term soil moisture difference is slightly negative, the comparison indicates that shortly after treatment, both water yield and soil moisture were higher than their long term value, and in the following 10 years, both declined somewhat. Water yield declined to a level lower than its long term value, and whilst likely, it can not be ascertained for certain whether the soil moisture difference did likewise.

As expected, a complimentary relationship was shown between soil moisture dynamics and long term water yield dynamics. The initial increase and subsequent decrease in soil moisture is an intermediate effect, caused by an initial decrease and subsequent increase in ET, and causing an initial increase and subsequent decrease in streamflow.

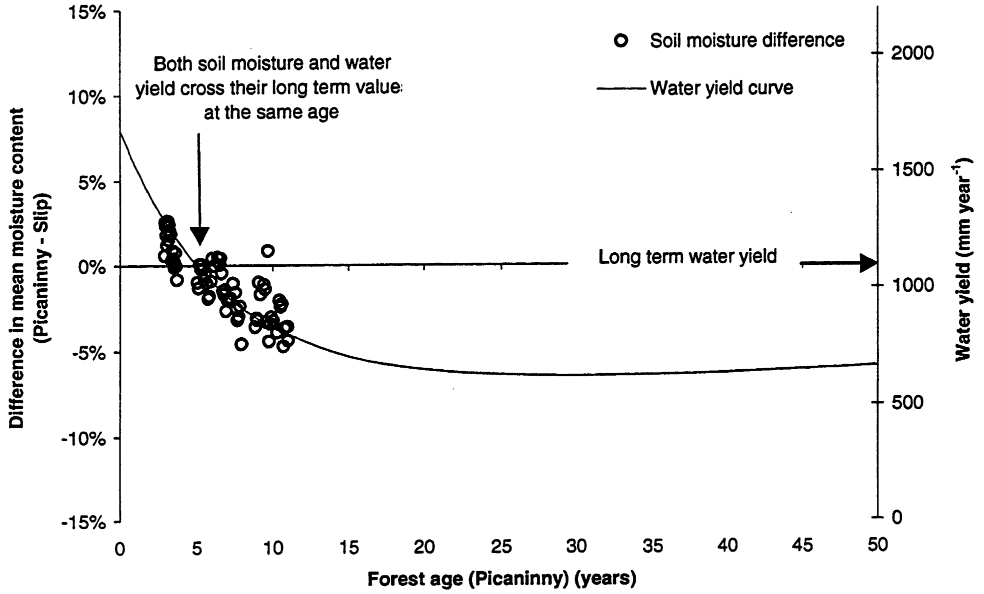

Figure 31: Effect of forestry on soil moisture over time: as for Figure 30 but represented within the context of long term changes in water yield (as in Figure 26).

7. Forest growth

7.1 Introduction

This section summarises the extensive forest growth data set of the Maroondah experimental programme, and conducts an analysis of the long term development of forest growth at Picaninny and Monda. Stem density and basal area are used as indicators of forest growth dynamics and are shown to respond clearly to forest treatment, thinning, growth, and insect infestation. The Picaninny data, in particular, show a clear relationship to long other long term data described in this report (such as water yield data). The Monda data reveal most clearly, the devastating effects of insect infestation.

7.2 Forest growth data

Permanent growth monitoring plots were set up in most of the experimental catchments. Initially all or a subset of these were surveyed every year or two. In recent years, the frequency has been reduced to once every three to five years. Figure 32 summarises the survey dates for each of the experimental catchments. Note that a number of catchments were additionally surveyed using non-permanent plots before and immediately after forest treatment. These surveys are not included in Figure 32 but are noted below.

At Coranderrk, a 1968 pre-treatment assessment was reported by Howard and O'Shaughnessy (1971). Post-treatment surveys were reported by Langford and O'Shaughnessy (1980b) and consisted of initial regeneration surveys from 1972, followed by permanent plot surveys from 1977.

Moran and O'Shaughnessy (1977) reported the first pre-treatment assessments at North Maroondah, consisting of 'stripline' surveys at Black Spur (1968), Monda (1969), Ettercon (1970 and 1973), and Myrtle (1970). The Ettercon growth data were also reported by Benyon (1992), covering initial assessments in 1970 and 1973, a pre-thinning inventory in 1981, and permanent plot measurements from 1982 onwards. At Monda, further pre-treatment assessments in 1977 were reported by O'Shaughnessy (1979). At Black Spur, further pre-treatment assessments in 1976 were reported by Aney and O'Shaughnessy (1994), followed by post-treatment assessments in permanent plots from 1977 to 1987. Aney and O'Shaughnessy (1994) are the only authors, to date, to report a continuous time series of growth measurements from the Maroondah work. Their analysis centred around the development of basal area increment as an indicator of growth in the decade following treatment at Black Spur. This was shown to vary around 1.0 $m^2ha^{-1}year^{-1}$ with relatively constant values in thinned catchments, but declining values in the control catchment.

At Crotty Creek, Incoll (1993) reported on the assessment of eight non-permanent plots from 1980 to 1990 prior to and following strip thinning treatment.

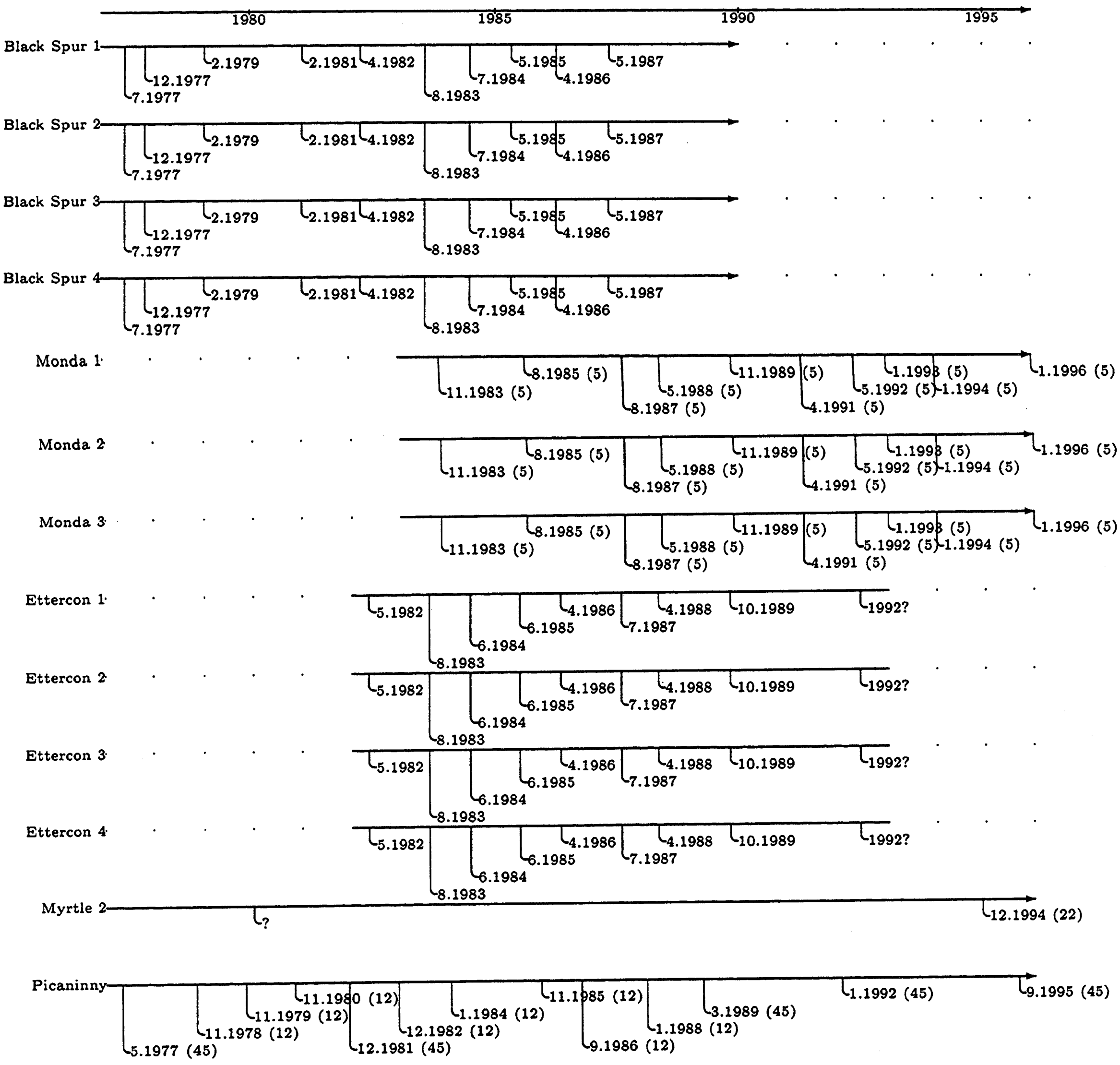

Figure 32: Dates of survey of permanent forest growth measurement plots in the Maroondah experimental catchments. Additional surveys were done, usually around the time of treatment, in non-permanent plots.

Each entry shows the month and year of survey. Where shown, parenthesised figures denote the number of plots which were surveyed.

The survey of a single plot involved the measurement of the diameter at breast height (DBH) of all stems in a fixed area, as well as the height of the two tallest trees. Further details are given in previous reports.

In the present work, the data for Picaninny and the Monda group were analysed. The data for Myrtle 2 were available in hardcopy form only and resources did not permit their digitisation within the time available.

It is worth noting that Melbourne Water has maintained an extensive continuous forest inventory (CFI) programme over the past few decades. Stem measurements were taken every ten years in some 500 plots within a wide variety of forest types scattered throughout Victoria's Central Highlands. These data have significant potential scientific and practical benefit and could contribute significantly to future analyses of Mountain Ash growth. The key to predicting the long term dynamics of forest water yield lies in quantifying long term forest growth dynamics relating to a wide range of forest types.

7.3 Analysis

Three summary variables were calculated to assess growth dynamics at Picaninny and Monda: the density of the forest in stems per hectare, the basal area (of stems at breast height) per hectare, and the annual increment in basal area. These were calculated at the catchment average level.

7.3.1 Picaninny

Picaninny has 12 plots which are measured at every survey, and a further 33 plots which are read less frequently (a total of 45 plots). Only the data from the 12 frequently read plots were used in the foregoing analysis. These data exhibit clear temporal patterns and are therefore satisfactory for the present analysis. The remaining data are suited to more detailed analyses such as the statistical characterisation of Ash forest growth conducted by Watson and Vertessy (1996). Digital data were available from 1981 to 1995. Further hardcopy data were available prior to 1977, but these were not used because of differences in the recording strategy employed in the younger forest.

Figure 33 shows the temporal development of the three summary variables introduced above with respect to forest age at Picaninny.

The plot of forest density includes a curve calculated for the Ash forests of the region by Watson and Vertessy (1996, Equation 13). Both Ash and mixed species forest at Picaninny have undergone thinning in their second decade of growth. There is little difference between the two, except that the Ash forest is perhaps thinning a little faster. The density of Ash at Picaninny is considerably lower than predicted for the region. This may be due partly to the fact that the Ash forest at Picaninny grows at the dry limit for the species (mean annual precipitation about 1000 mm). It may also be due to delays in the establishment of the forest caused by extensive wallaby foraging (O'Shaughnessy, 1980).

Basal area at Picaninny increased steadily from 10 to 20 years of age at approximately the same rate for both Ash and mixed species forest. Although, prior to the period for which digital data were available, the mixed species forest was delayed relative to the Ash before reaching a steady growth rate. At 15 years of age, there was a decline in the rate of basal area increment for Ash and an increase for mixed species. This corresponds with the peak in LAI and the dip in water yield (Figure 1) in Ash forests at around 5 to 10 years of age.

In general, the growth observed at Picaninny is similar to the expected pattern of Mountain Ash forest growth described in the introduction.

7.3.2 Monda

Five permanent plots were established in each of the three treated Monda catchments and were surveyed every year or two from 1983. The most recent survey was in 1996.

Figure 34 shows the development of forest growth at Monda as indicated by stem density, basal area, and basal area increment. The density plot reveals some interesting dynamics.

Monda 2 was planted with the highest density of seedlings (seed scattered to achieve *at least* 5000 seedlings ha^{-1}, probably closer to 10 000). By five years of age, exhibited over 8000 stems per hectare, which is close to the value predicted by the regional curve. Natural regeneration must have supplemented the planting considerably. Beetham (1950) recorded natural Mountain Ash regeneration of 2.4×10^6 seedlings per hectare at Noojee, Victoria. Monda 1 was planted with 2000 seedlings per hectare, and after five years, retained this density. It is possible that natural regeneration also occurred, and that thinning had reduced the total back to 2000 ha^{-1} by five years of age. Monda 3 had the most sparse stocking (nominally 500 seedlings ha^{-1}), and by five years of age, nearly 700 stems ha^{-1} were recorded.

It appears that, for each of the Monda catchments, the medium term density of stems was controlled largely by the planting density, but that in each case, the stocking was supplemented by additional natural regeneration. This conclusion may possibly be confounded if the initial estimate of planting density was incorrect, or if the survey plots are unrepresentative of the catchments as a whole.

In all three catchments, thinning and growth continued beyond five years

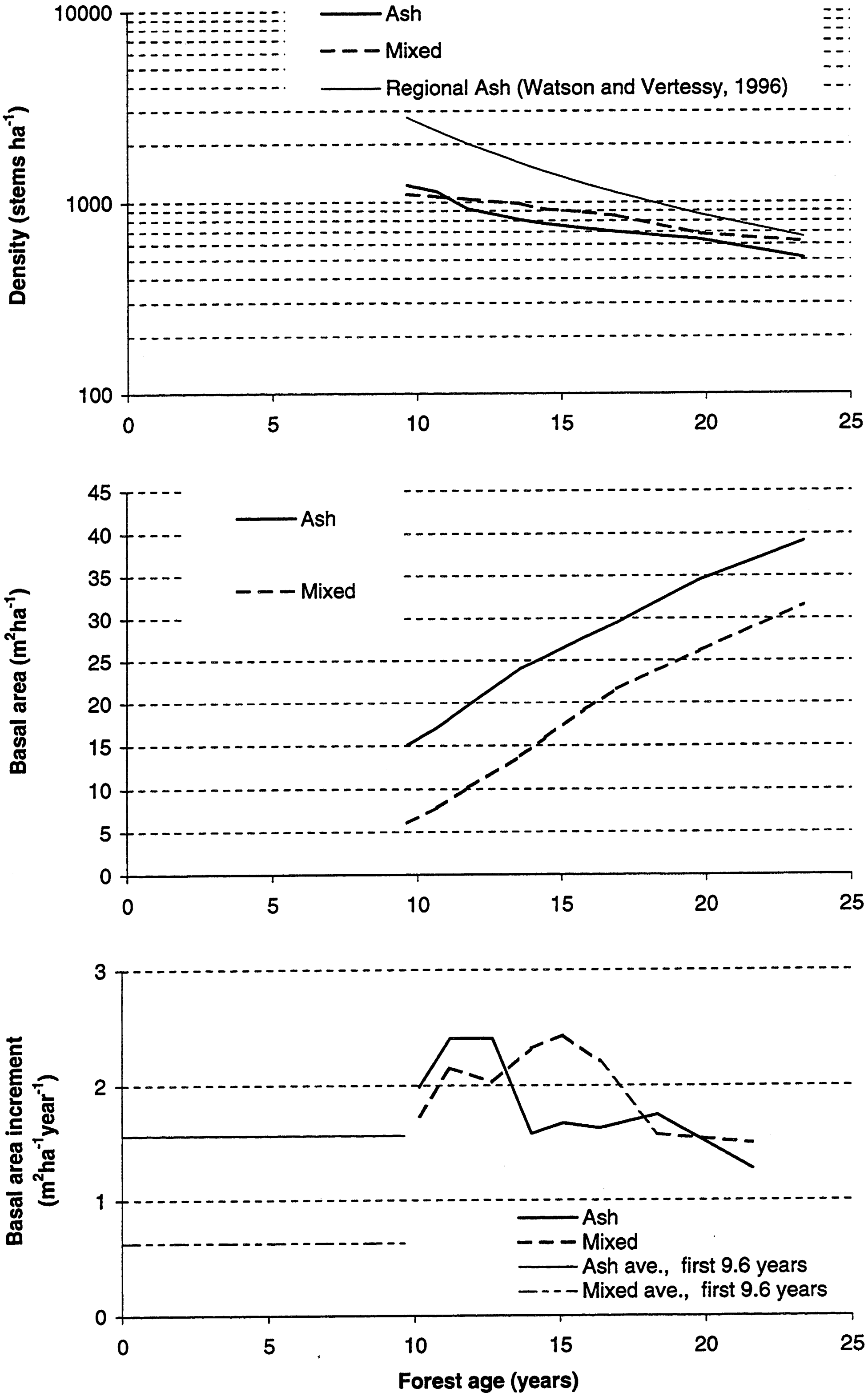

Figure 33: Progression of forest thinning and growth at Picaninny.

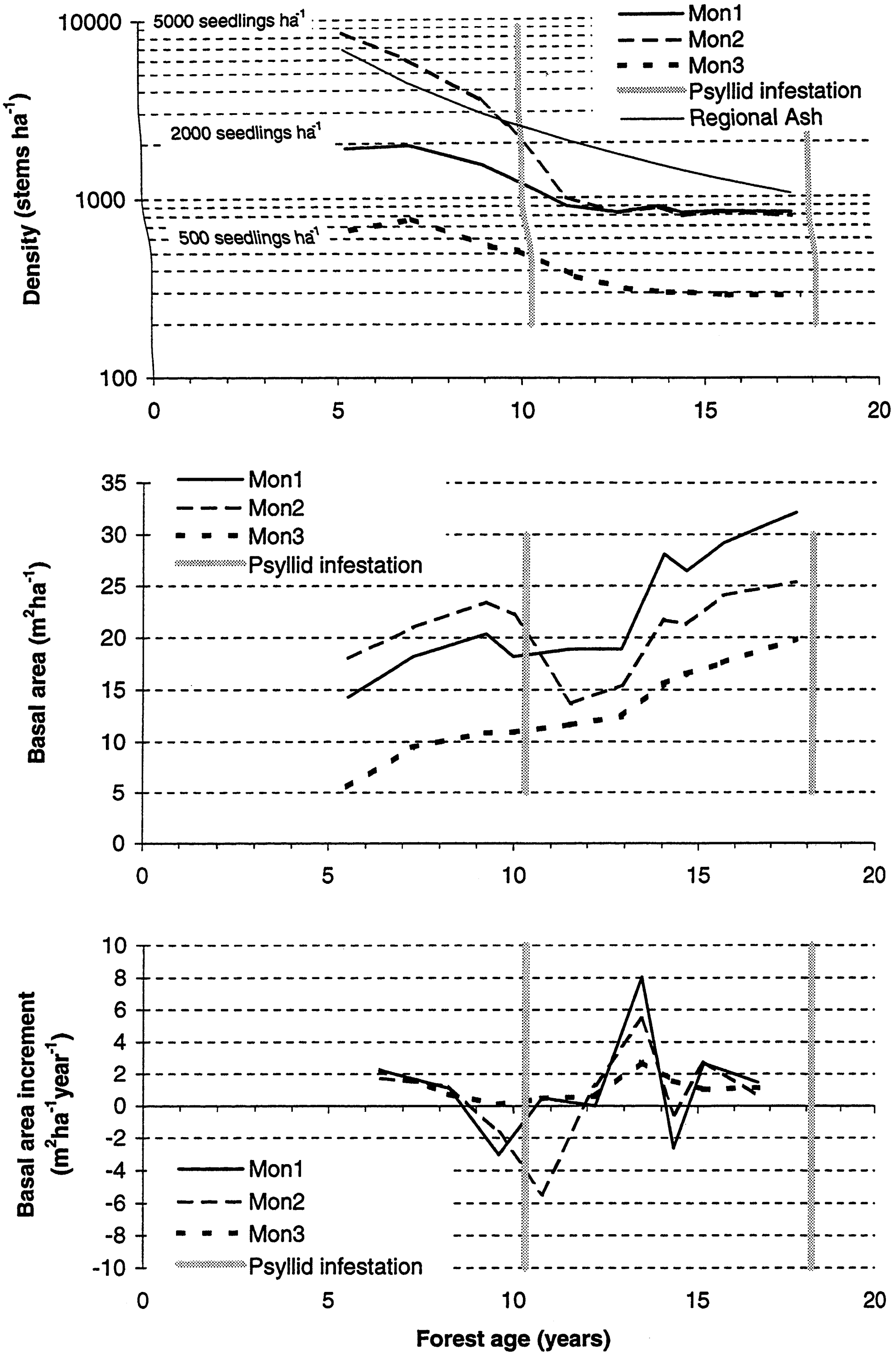

Figure 34: Progression of forest thinning and growth at Monda.

of age in an expected manner only for a short time. Culminating with the noticing of Psyllid infestation in 1988 when the forest was 10 years of age, stem density dropped sharply and growth became negative at Monda 1 and Monda 2 (particularly at Monda 2). This is striking evidence of the dieback of the forest caused by the Psyllids and strengthens the argument that the abnormal water yield patterns at Monda were caused by the Psyllids.

Immediately following 1988, growth increased to well above pre-infestation levels, and well above that observed at Picaninny. This suggests that either all of or a significant part of the forest entered a vigorous regeneration period of the kind expected immediately following complete clearing. At about 14 years of age, the regeneration was curtailed for unexplained reasons and has since appeared to stabilise.

The 1996 Psyllid infestation post-dates the most recent survey of the Monda group.

8. Interception

8.1 Introduction

This section summarises the precipitation interception data of the Maroondah experimental programme, and analyses that data which best reveal long term trends resulting from forest treatment. The Picaninny data, in particular, relate well to concomitant trends in forest growth and water yield, and confirm the strong influence of changes in interception in explaining changes in water yield.

8.2 Throughfall data

Throughfall measurement plots were set up a in number of the experimental catchments, as summarised in Figure 35. Haydon et al. (1996) brought together much of the Maroondah interception data in an analysis of long term interception trends for forests aged zero to 244 years old. Their work yielded a long term curve of interception versus forest age which appears qualitatively similar to the LAI curves presented in the introduction. As for analyses of data from specific catchments, the Black Spur data were analysed by Jayasuriya and Aney (1994), the Ettercon 4 data are yet to be analysed, and a variety of data from the Coranderrk group were analysed by Langford and O'Shaughnessy (1978). The present work analyses the latest Picaninny and Monda data. The short records at Myrtle 1 and Myrtle 2 were a lower priority and were not examined.

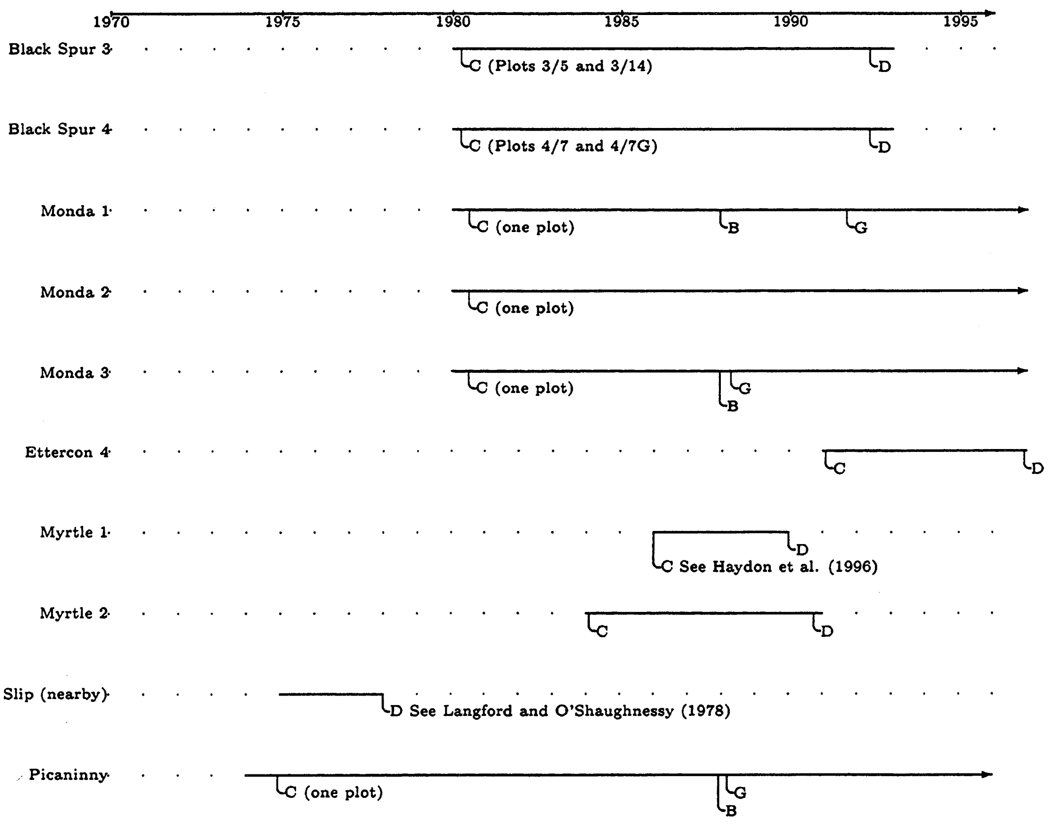

Figure 35: Commencement and, where applicable, decommissioning of troughfall measurement plots in the Maroondah experimental catchments. C = Commencement, B = Ban on tower precip. gauges, G = Ground precip. gauge record commences, D = Decommissioning.

The Picaninny data include one of the longest throughfall data sets in existence. For the present study, they were obtained as a series of measurements of precipitation (in mm) and throughfall from two drums (also in mm). The data for each drum having been converted from litres to millimetres as part of the record keeping process. Each drum was attached to five throughfall throughs. Readings were taken from late 1974 to late 1996, initially about once per week, and later about once every two weeks. Many data entries were accompanied by notes about leaking, blocked, frozen, damaged, or vandalised instrumentation. According to judgement about the severity of the problem, such entries were discarded from the analysis. Initially, the accompanying precipitation data were from a 12.2 metre tower-mounted gauge (Duncan, 1980). However, in late 1987, the towers were deemed too dangerous and ground gauges were used from the 14th of December 1987.

The Monda data comprised a separate precipitation and throughfall record for each catchment. The throughfall data were obtained as plot totals in litres, where each plot contained six drums with two troughs each. A conversion equation, calibrated for troughs at Blacks Spur (O'Shaughnessy and Jayasuriya, 1994, p. 71), was used to convert litres to millimetres:

$$\mathrm{mm} = 1.222 \times \frac{\text{litres}}{\text{no. of troughs}} - 1.3607 \tag{23}$$

At Monda, readings were taken from mid 1980 to late 1996, typically once every one to two weeks. As with the Picaninny data, there were numerous notes placed against records. However, in many cases, these related to apparently minor incidents pertaining to only one or two of the 12 troughs in each plot and so only the more severely affected records were eliminated from the analysis. The precipitation gauges for the Monda 1, 2, and 3 plots were located at North Maroondah Sites 2, 20, and 21 respectively. Site 20 was always a ground gauge, whilst the other two were initially tower-mounted and later replaced with ground gauges. With the onset of bans on tower measurements, numerous data were missing from early 1988. A ground gauge was adopted for use at Monda 3 on 6th April 1988, but the precipitation record for the Monda 1 plot remained blank for several years until September 20, 1991.

8.3 Analysis

8.3.1 Picaninny

To convert the precipitation and throughfall data to interception measurements, the following steps were taken. Firstly, the throughfall data were adjusted to allow for differences between the mean precipitation recorded

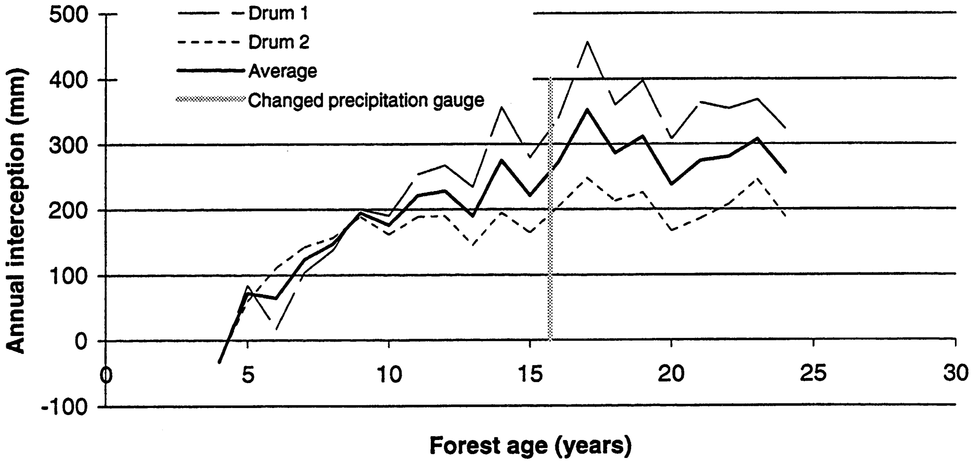

Figure 36: Time series of precipitation interception at Picaninny.

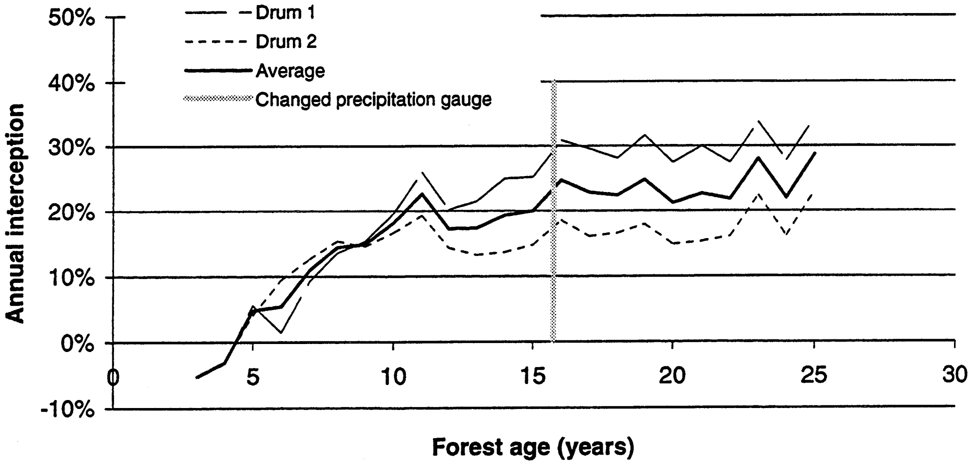

Figure 37: Time series of precipitation interception at Picaninny, expressed as a percentage of precipitation.

by the throughfall troughs under no vegetation cover, and that recorded by the precipitation gauges. The adjustment equations were inferred from earlier data for the site presented in Table 6.1 of Langford and O'Shaughnessy (1980b). Interception for a given measurement period was taken to be precipitation minus stemflow minus throughfall. Stemflow was assumed to be five percent of precipitation, after Langford and O'Shaughnessy (1978, Tab. 14). The resulting data were highly variable (CV = 0.69), so annual averages were taken as follows. The age of the forest at each measurement was calculated and rounded to the nearest integer, then the total precipitation and interception corresponding to each integral age value was calculated. Annual interception in mm is plotted in Figure 36. Because of missing data, some totals were not always for an entire year. These are omitted from Figure 36, but are included in Figure 37, which plots interception as a percentage of precipitation.

The plots show that there is some variation between the two drums, presumably associated with variable vegetation cover, but that they are generally consistent in temporal pattern. Therefore, an average from the two drums is plotted. At ages three and four, negative interception is indicated. This implies that, despite the adjustment of throughfall data described above, there remains some discrepancy between precipitation and throughfall measurement. Possible reasons for this include random climate variability, as well as a changing aerodynamic environment around the throughfall troughs as the forest developed. Immediately after the nil vegetation period during which the adjustment equations were developed, low vegetation would have surrounded the troughs, sheltering them from wind and favouring greater throughfall collection, leading to lower, possibly negative interception values. An uncertainty of about 5% therefore surrounds the interception values plotted in Figure 37.

The long term development of interception at Picaninny was as expected, based on leaf area index data presented earlier in this report. Interception starts at zero, and after some delay associated with poor regeneration at Picaninny, rises to values over 20% at about 10 to 15 years of age. After 25 years, there is some indication of a decline in the absolute data, but not in the percentage data. The pattern described by Haydon et al. (1996), and based on data from the wider Central Highlands region, predicts a peak of about 25% at 30 years of age, which may be the eventual pattern observed at Picaninny.

The consistency of the precipitation data after changing from a tower-mounted to a ground gauge was validated by calculating the total precipitation pre- and post-change as a percentage of total precipitation from the same two periods at the nearby Lower Coranderrk long term meteorological station. The two percentages differed by only 0.3%, and so the record was considered to be consistent with no impact on the interception values.

With regard to the role of interception in the overall water balance of Ash forests, the data support earlier findings. The decline in water yield at Picaninny observed after about 10 years of age can be attributed in part to increased interception of precipitation, in addition to increased transpiration as implied by the forest growth data.

8.3.2 Monda

The analysis of the Monda data was carried out as for the Picaninny data, and the absolute and percentage results are presented in Figures 38 and 39 respectively. The gaps in Figures 38 are due to frequent missing data.

The patterns evident for Monda support the Picaninny results, but differ in some aspects. Interception at all plots starts at zero and then rises quite rapidly to between about 20% and 30% within 5 years. Between 5 and 10

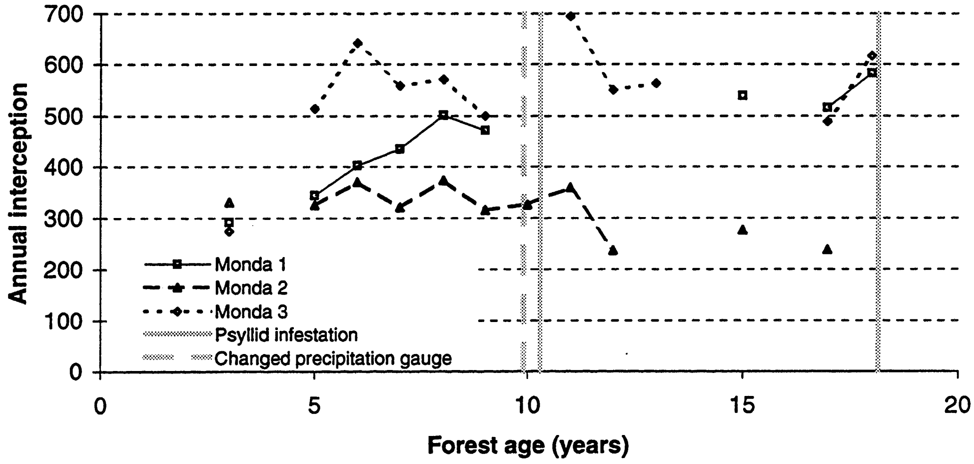

Figure 38: Time series of precipitation interception at Monda.

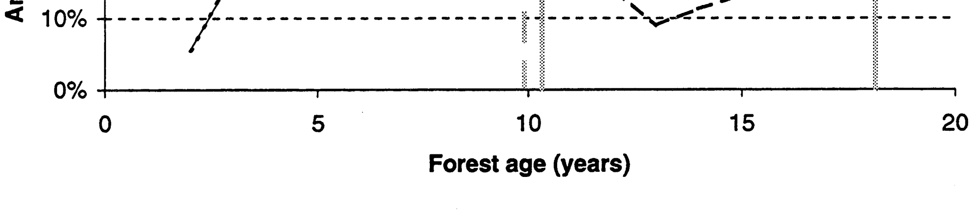

Figure 39: Time series of precipitation interception at Monda, expressed as a percentage of precipitation.

years of age, the highest interception is observed at Monda 3, followed by Monda 1, and then Monda 2. This is the reverse to the ordering of basal area in this period (Figure 34), a fact which is unexplained.

Following the time at which the 1988 Psyllid infestation was first observed, interception at the Monda 2 plot declined, whereas the other plots were relatively unaffected. Trends in the forest growth data (Figure 34) also suggest that Monda 2 was the catchment most affected. However, the decline of interception after infestation is more gradual than the corresponding decline in forest growth (Figure 34) and increase in water yield (Figure 21). This may be due to the fact that dead leaves and branches persist and are able to intercept precipitation for some time after they have died, and also because of the persistent interception by understorey species, which are significant in these catchments.

After about 15 years of age, there is no clear pattern in the Monda data, with interception at this time presumably being subject to the conflicting and varying influences of natural reduction in leaf area, regeneration following infestation, and the delayed shedding of dead material.

It should be noted that inter-comparison between analyses of water yield, forest growth, and precipitation interception at Monda is likely to be confounded to some extent by spatial variability of forest cover and infestation between *and within* the three treated catchments. The locations of the growth and interception plots do not necessarily reflect conditions across the catchment.

9. Summary

9.1 Introduction

Hydrologic and biometric data from three groups of catchments subject to experimental forestry treatments (Myrtle, Monda, and Coranderrk) were analysed. The analyses which were conducted related to water yield, long term water yield, low flow duration, soil moisture, forest growth, and precipitation interception. Once both short and long term effects on water yield of forest treatment were established and described, the effect of treatment on the other variables (moisture, growth, and interception) was described and placed in the context of explanation of long term trends in water yield. These steps are summarised below.

9.2 Water yield

The primary analysis examined hydrographic data in order to ascertain the effect of the forestry treatments on water yield. For this purpose, a detailed statistical procedure was developed using time series analysis techniques. A regression model was constructed which predicted water yield at treated catchments from water yield at control catchments. The model involved a multiple regression between log-transformed monthly water yield data from treated and control catchments, with a trigonometric seasonal component as an additional independent variable, and a final lag-one auto-regressive (AR1) model of the residuals. The resulting 'disturbances' were shown to be independent, non-seasonal, homoscedastic, uniformly distributed in x, and normally distributed in y. Thus 95% confidence limits could be calculated, such that where more than 5% of disturbances fell outside the limits, a statistically significant treatment effect was implied. Once this significance had been established, the actual magnitude of the treatment effect was determined by re-linearising the residuals back into the linear domain. By comparison of results, the method was shown to have similar power to water balance modelling approaches, but with fewer parameters and reduced complexity.

The statistical approach adopted here is not commonly used in paired catchment studies, which typically use annually based analyses. The use of monthly data with an explicit seasonal component in the regression allows more data points to be used in the pre-treatment calibration period, and thus strengthens the statistical validity of the analysis. A number of studies have presented regression analyses including confidence limits without formal validation of the inherent assumptions. The present study shows that such validation is not only warranted, but that corrections and transformations may be necessary. Confidence in the present results was derived from explicit testing for uniformity, homoscedasticity, independence, and normality using devices such as correlograms and Kolmogorov-Smirnov plots.

The results for the Myrtle group showed a clear treatment effect, with an increase in water yield for 2-3 years following treatment, falling to a decrease in water yield by about 10 years after treatment. It was uncertain whether a recovery toward pre-treatment yields had begun in the most recently acquired data (12 years of age).

The results for the Monda group began similarly, with a dramatic short term increase in water yield. But at the age when decreased yield would be expected, the first of two Psyllid insect infestations occurred causing forest dieback and subsequent regeneration. Expected declines in water yield were negated by high yield from the regenerating forest and consequently, none of the Monda catchments had reached or appeared likely to reach a period of decreased water yield by 19 years of age.

Picaninny responded to clearfelling in a similar manner to Myrtle 2, but more slowly. The initial increase was rapid, but yields approaching minimum values did not occur until about 15 years of age. This was explained by the poor initial regeneration of forest at Picaninny. Again, it was uncertain whether a recovery to pre-treatment yields had begun by the end of the current record (25 years of age).

9.3 Long term water yield

To facilitate a comparison of the water yield data from all of the subject experimental catchments, a simple, one store water balance model was constructed. The model represents the simplest possible structure for a one store model and can be cast as a regression and calibrated by least squares. Inputs to the model are catchment precipitation and water yield. The output is an estimate of catchment evapotranspiration (ET).

The model was applied to each of the catchments using, as input data, catchment average precipitation calculated by using the precipitation record from Lower Coranderrk to modulate previously estimated catchment mean annual precipitation values. Time series of estimated ET for the catchments were overlaid and found to align, approximately, along a single curve. The curve showed an instantaneous drop in ET immediately following forest clearing, followed by a fairly rapid increase to a peak around 20 to 40 years of age. This was followed by a gradual decline over the next 100 or so years to a long term climax value. The curve is an encouraging unification of water balance observations from a number of catchments.

An idealised mathematical curve was fitted to the data and subtracted from a constant precipitation value to give an estimated regional long term water yield curve. This was shown to be similar to the Kuczera curve, but with additional features such as a predicted increase in yield in the first five years. The general correspondence with the Kuczera curve is encouraging, given the differences in scale and method behind the two curves. A broad dip in water yield between about 20 and 40 years of age suggests that recovery to pre-treatment water yield may only be just beginning in the experimental catchments. Whilst the two curves differed in their predictions of the time to water yield recovery, qualifications were placed on the significance these differences due to the subjective nature of the new curve and the differences in scale and method underlying the two curves.

9.4 Low flow duration

Flow duration curves were calculated in five year blocks for all catchments. Examination of these curves revealed that, in all but one case, changes in overall water yield were manifest uniformly over all percentile flows. The exception was the driest catchment, Picaninny, where low flows occurred significantly more often during the period of reduced water yield than would be expected if all percentile flows were reduced evenly. In all cases, climatic variability between five year blocks equalled or exceeded variability due to forestry treatments, making analyses of changes in flow duration difficult.

9.5 Soil moisture

Analysis of soil moisture data was restricted to the Picaninny and Slip catchments. Catchment averaged data from numerous boreholes within each catchment clearly showed a reduction in soil moisture associated with treatment at Picaninny. The reduction aligned well with concurrent changes in water yield. The data form a useful measured, physical, intermediate link between increased forest evapotranspiration in regrowth forest, and consequent reduced streamflow.

9.6 Forest growth

Melbourne Water holds a valuable and extensive array of forest growth data, a small fraction of which was able to be analysed in the present study. Based on stem diameter surveys made every few years, curves were presented of stem density, basal area, and basal area increment for the Picaninny catchment and the Monda catchments.

The Picaninny data followed the expected model of forest growth, with a steady thinning of stems and absolute stem density slightly below the regional mean (which applies to generally wetter forest). Basal area increment was also steady, although there was some evidence of a peak at around 10 years of age for Mountain Ash. More data are available and should be used to confirm this.

The Monda data reflected earlier observations relating to the Psyllid infestations. Stem densities appeared to be dependent on initial planting densities, but were also affected by natural regeneration, thinning, and insect infestation. The 1988 infestation had a large impact on basal area, whereby the mean annual increment became negative for two years in the case of Monda 2. Monda 1 was also affected, and Monda 3 less so. Reverberations of the infestation were apparent in following years with some very high basal area increments, as well as some negative ones.

9.7 Precipitation interception

Long term throughfall data sets were available at Picaninny and Monda. These were cleaned, converted to estimates of precipitation interception, and aggregated to annual values by forest age.

The Picaninny data follow an expected pattern which matches the previously described patterns of water yield, soil moisture, and forest growth. After a slow beginning, interception rises to over 20% by 10 to 15 years of age, after which time no clear increase or decrease is indicated by 25 years of age. Potentially about 5% error in the data is associated with uncertainty in the nil vegetation calibration between precipitation and throughfall gauges. Precipitation gauging was moved from being tower-based to being ground-based, but this did not alter the total recorded precipitation relative to a nearby site, and so no further error was introduced.

The Monda data reveal more complicated patterns of interception dynamics. Interception in all of the catchments increased to about 20% to 30% by about 5 to 10 years of age. There are significant differences between the catchments, which may only be explained by local variability in forest cover. The interception plot at Monda 2 is the only one noticeably affected by the 1988 Psyllid infestation. Interestingly, the response is slow, presumably due to retention of dead leaves and branches for some time after death. The other plots appear relatively unaffected, although the one at Monda 3 may be affected by the 1996 infestation. The results are inconclusive.

10. Conclusion

Whilst regressions between treated and control catchments can, in any circumstances, be used to quantify the impacts of forestry on water yield, certain statistical constraints must be met if statistical significance is to be attributed to such quantification. In some cases, data transformations and modifications to standard regression models are necessary to ensure such constraints are met. Un-biased estimation of regression coefficients is possible only with uniformly distributed samples, and prediction intervals should only be placed around model residuals or disturbances once their homoscedacity, normality, and independence has been established. In cases where pre-treatment records are short, monthly based analyses are preferable to annual ones because of the twelve times larger sample size, at the cost of only two or three additional parameters needed to account for seasonal variation and any additional serial correlation.

With respect to the Maroondah catchments, it is clear that in two cases, Myrtle and Coranderrk, a statistically significant medium term reduction in streamflow has occurred. This is an encouraging indication that previously known long term regional trends are evident at the scale of small experimental catchments. It is recommended that observations continue in order that the time to recovery may be quantified. The observations of dieback and lack of expected treatment effects at Monda indicates that defoliation by insects is a significant influence on water yield in these forests.

There is evidence to suggest that in the driest Mountain Ash forests, low flows are lessened more by forest regeneration than mean flows.

Temporal patterns of water yield can be related to temporal patterns in controlling factors within the forest, such as forest growth, precipitation interception, and soil moisture.

Further work should re-examine long term curves for water yield versus age. The Kuczera analysis could be repeated or updated using about 15 years of additional data. Also, the synthesis of small catchment water balance models developed in this report could be extended to provide a more objective unifying curve with error characterisation and some account of differing treated fractions. This could lead to work on reconciling the differences between the large and small catchment analyses.

Such work would support physically based modelling efforts which should be able to reproduce Kuczera or equvalent curves for any part of the Ash Forest.

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