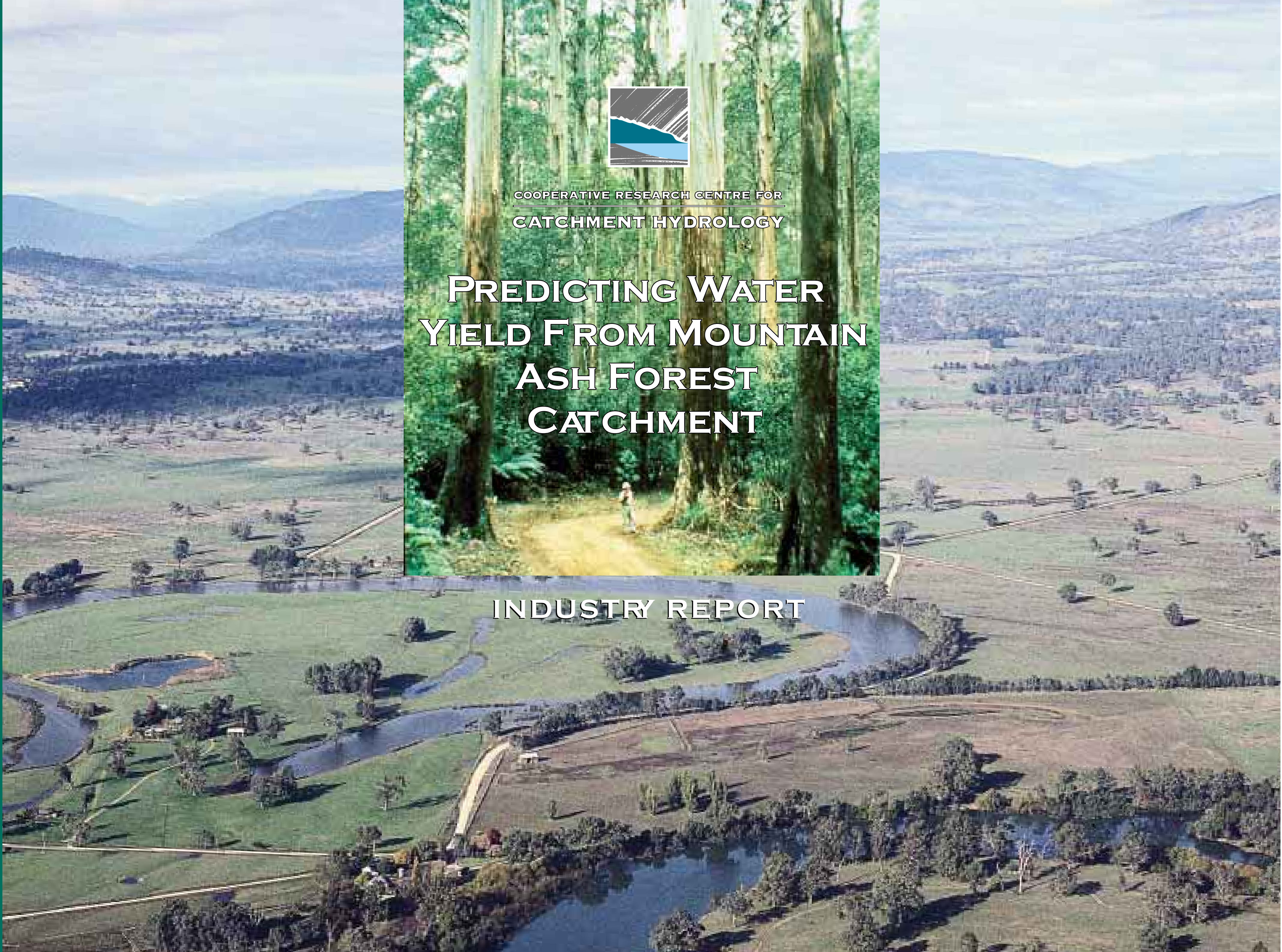


COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

Predicting Water Yield From Mountain Ash Forest Catchment

INDUSTRY REPORT

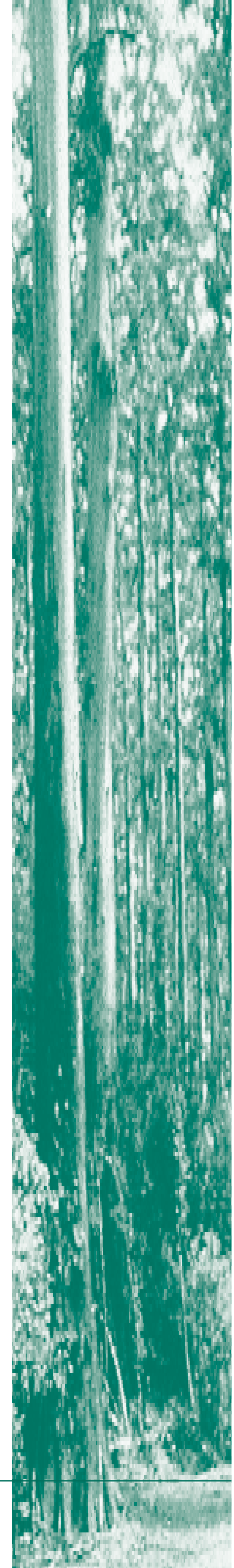
Predicting Water Yield From Mountain Ash Forest Catchments

by

Robert Vertessy, Fred Watson, Sharon O'Sullivan,

Sharon Davis, Richard Campbell,

Richard Benyon and Shane Haydon



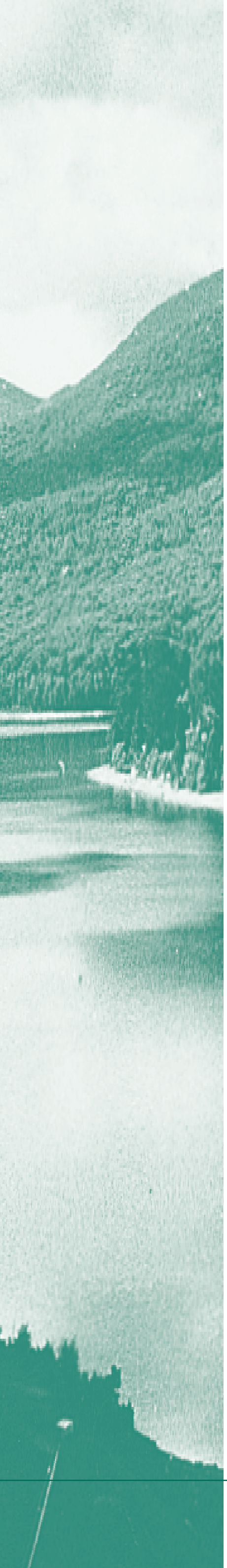
COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

Industry Report

Report 98/4

April 1998



Vertessy, R.
Predicting water yield from mountain ash forest catchments.

Bibliography
ISBN 1 876006 30 7.
1. Watershed management – Victoria – Maroondah Reservoir Region.
2. Hydrology, Forest – Victoria – Maroondah Reservoir Region.
I. Vertessy, R.A. (Robert Alexander). 1961– .
II. Cooperative Research Centre for Catchment Hydrology. (Series: Report (Cooperative Research Centre for Catchment Hydrology); 98/4).

551.48099452

Keywords

Water Yields
Forests
Catchment Areas
Modelling (Hydrological)
Rainfall/Runoff Relationship
Water Balance
Evapotranspiration
Topog
Macaque
Forecasting
Fires

Background cover photo: Aerial view of Murray River billabong near Albury, NSW.

Cooperative Research Centre for Catchment Hydrology
Centre Office–Department of Civil Engineering
Monash University, Clayton
Victoria 3168, Australia
Phone: (03) 9905 2704
Fax: (03) 9905 5033
Home page: http://www-civil.eng.monash.edu.au/centres/crcch/

Photographs were provided by:

- Sharon Davis
- David McJannet
- Pat O'Shaughnessy
- Ian Rutherford
- Jack Snodgrass
- Rob Vertessy
- Fred Watson

F o r e w o r d

This Industry Report is one of a series prepared by the Cooperative Research Centre (CRC) for Catchment Hydrology to help provide agencies and consultants in the Australian land and water industry with improved ways of managing catchments.

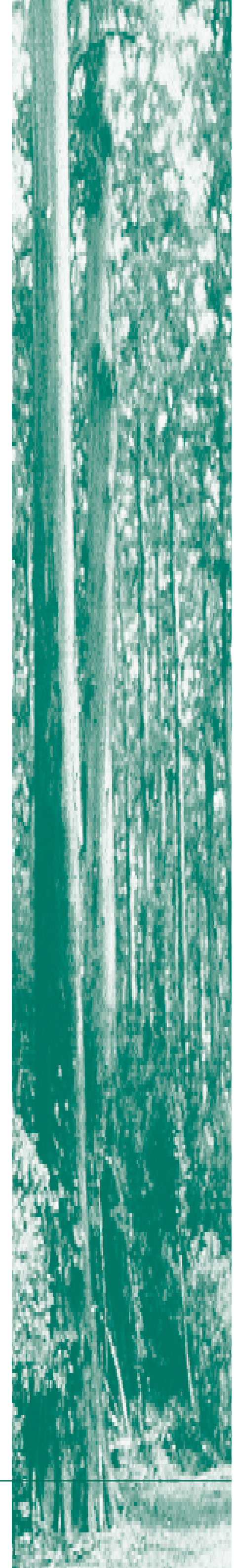
Through this series of reports and other forms of technology transfer, industry is now able to benefit from the Centre's high-quality, comprehensive research on salinity, forest hydrology, waterway management, urban hydrology and flood hydrology.

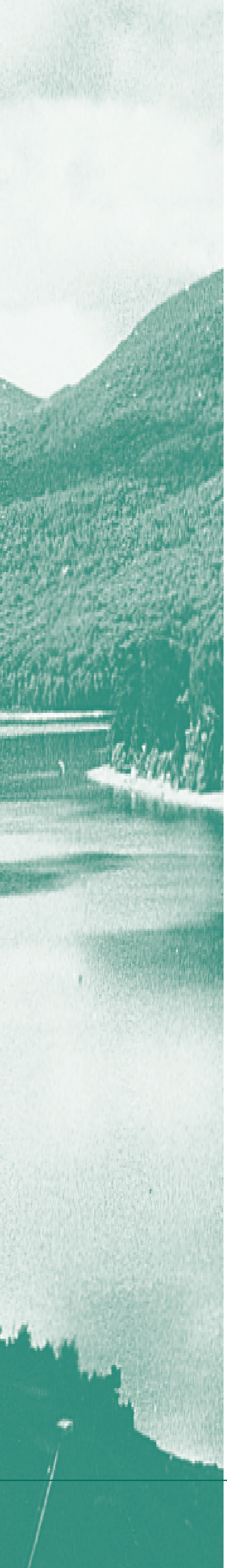
This particular Report represents a major contribution from the CRC's forest hydrology program, and presents key findings from the project entitled 'Development and evaluation of predictive tools for water production in natural, disturbed and managed forests'. (More detailed explanations and research findings from the project can be found in a separate series of Research Reports and Working Documents published by the Centre.)

The CRC welcomes feedback on the work reported here, and is keen to discuss opportunities for further collaboration with industry to expedite the process of getting research outcomes into practice.

Russell Mein

Director, CRC for Catchment Hydrology





Preface

In this report, we have summarised the outcomes of the Cooperative Research Centre (CRC) for Catchment Hydrology's Project A2, entitled 'Development and evaluation of predictive tools for water production in natural, disturbed and managed forests'. The aim of the project was to build computer models for use in predicting how water yield from forest catchments would change if logging, fire, species replacement or natural ageing modified the forest cover.

As well as computer modelling, we carried out a large number of field experiments. The objective was to clarify forest hydrological processes that were previously poorly understood and to provide test data for our models. We chose to focus most of this work on the mountain ash (*Eucalyptus regnans*) in the forested water supply catchments northeast of Melbourne, Victoria.

This report provides a broader summary of our research findings than has been presented in scientific journal papers and academic theses (see 'Further Reading' section).

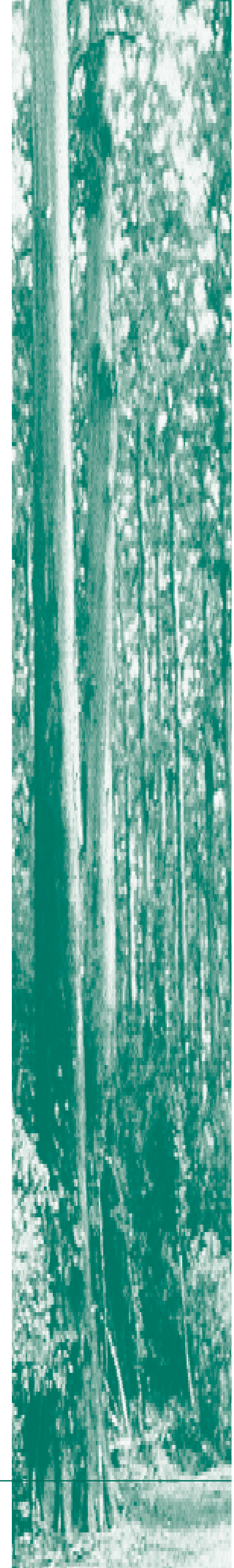
Acknowledgments

Many researchers assisted the authors in this study between 1993 and 1997, including Ian Watson, Jack Snodgrass, Alan Godenzi, Gary Winter, Tony Butt, Craig Beverly, Richard Silberstein, Jim Brophy, Jamie Margules, Peter Reece, Tom Hatton, Neil McKenzie, Mike Papworth, Alicia Lucas, Richard Hartland, Jim Morris, John Collopy, Nigel Tapper, Russell Mein, Tom McMahon, David Dunkerley, Paul Gribben, Marek Komarzynski, Sam Dasberg, Helmut Elsenbeer, Larry Band, Axing Zhu and Zook. Several postgraduate students were also involved, including David McJannet, Daniel Lorieri, Peter Steveling, Andreas Lack, Robyn Chiswell, Campbell Pfeiffer, Sam Green, Jason Berringer, Judi Buckmaster, Russell Wild and Yves Bessard. These students helped to make the project a real joy to run.

The project benefited greatly through input from Reference Panel members David Flinn, Pat O'Shaughnessy, Dasarath Jayasuriya, Peter Attiwill and Leon Bren.

We thank David Perry and Mary-Lou Considine for their careful editing of the original manuscipt. Keith Mitchell, Kay Dancey and Daniel Figucio are to be congratulated for doing such a fine job with the diagrams.

Contents



Mature mountain ash forest, aged 150 years, Yarra Ranges National Park

BACKGROUND

WATER PRODUCTION FROM FORESTS

Forest hydrology is the science of how water moves through forested ecosystems (Figure 1). Apart from being a fascinating topic for researchers, it is of practical importance to the wider community because the drinking water for many large cities like Melbourne comes from forested areas.

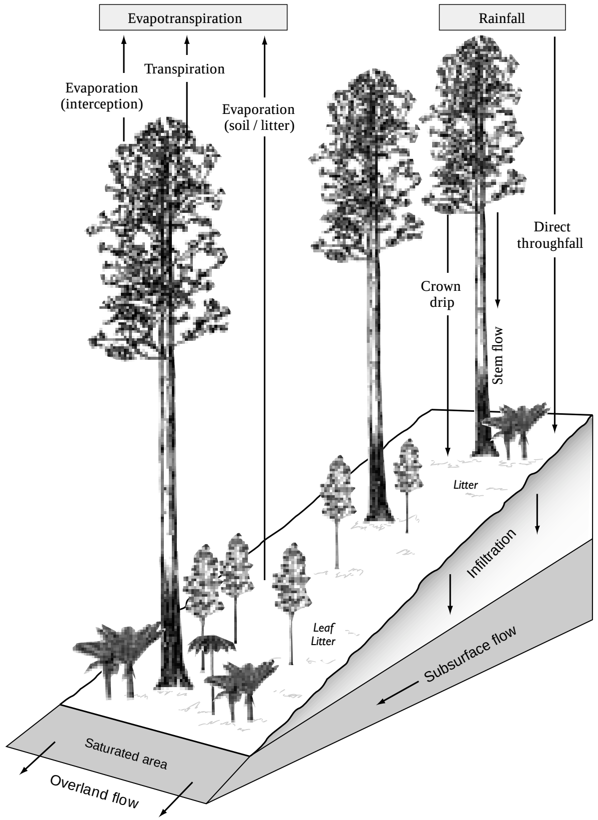


Figure 1: Key hydrological processes on a forested hillslope.

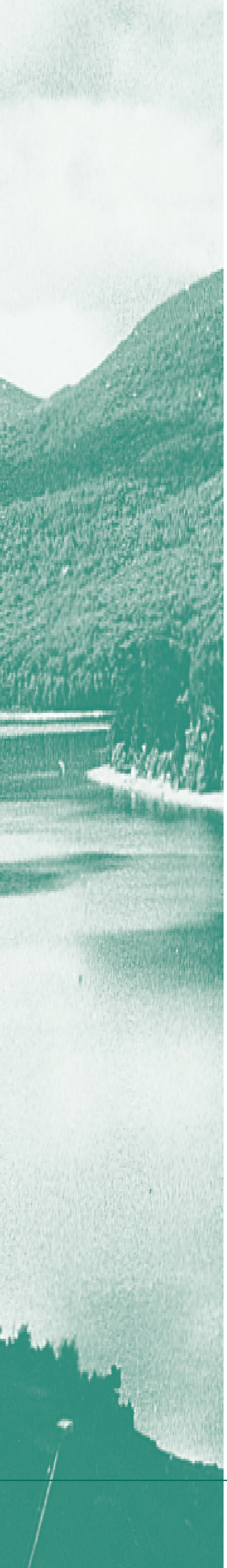
Forestry operations in reservoir catchments are of concern to water managers.

However, the same forests are harvested for timber and are susceptible to natural disturbances like fire and climate change. We need to know how such disturbances affect the quantity and quality of runoff from catchments.

The conventional way for hydrologists to assess how forests affect water movement through catchments (the water balance) is to perform a catchment experiment. Two different types of experiment have been used:

- Single catchment treatment experiments–a catchment is initially monitored, then treated and monitored further to record the effects of treatment.
- Paired catchment treatment experiments–two catchments are initially monitored, before one is treated; further monitoring of both reveals possible changes in the treated catchment relative to the untreated one (the 'control').

Researchers have conducted many such experimental catchment treatments



throughout the world, with key Australian examples occurring in the Maroondah, Yambulla, Karuah, Babinda, Collie and Darling Ranges catchments (Figure 2). 'Treatments' have included a range of logging regimes, afforestation and species changes.

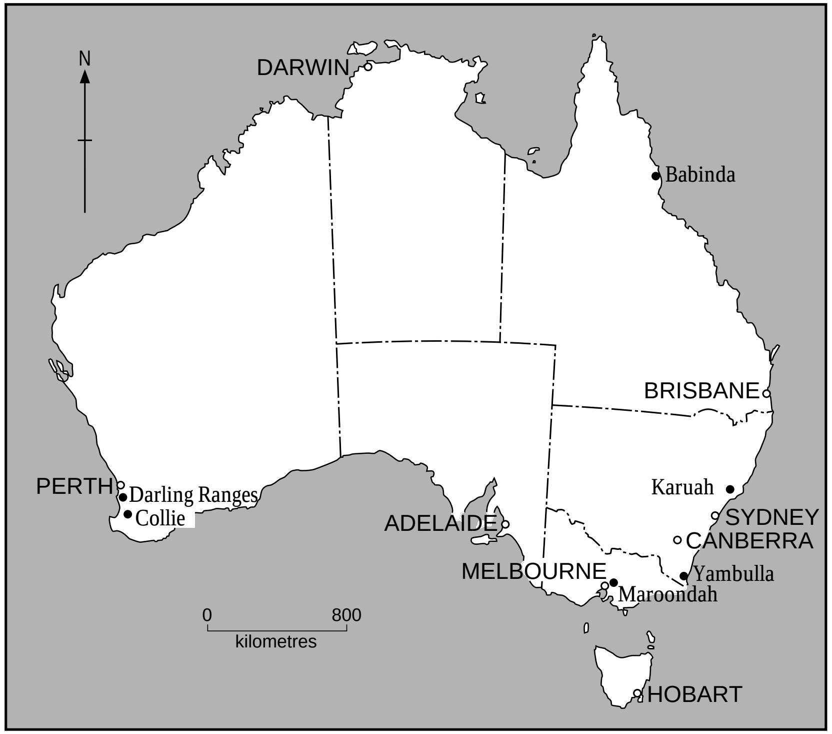
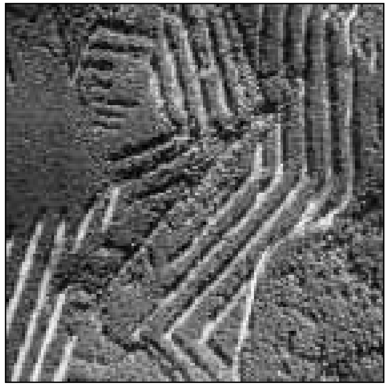


Figure 2: Locations of major catchment treatment experiments in Australia.

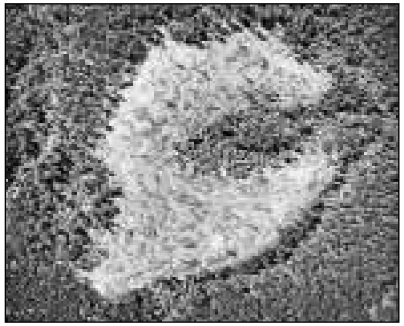
Typical flow gauging structure used in catchment treatment experiments.

Above: Removal of a mature mountain ash tree from a logging coupe.



Right: Strip thinning experiment conducted by Melbourne Water and DNRE at the Crotty Creek catchment.

Below: Old growth clearfelling experiment, Myrtle-2 catchment, Yarra Ranges National Park.



Different thinning experiments performed by Melbourne Water in the Black Spur group of catch-ments, Yarra Ranges National Park.

What do we know about the hydrologic effects of forest change?

While the response of catchments to changes in forest cover is variable, the following generalisations can be made:

- A reduction in forest cover produces a rise in water yield and a rise in stormflow runoff peaks. Conversely, when forest cover is increased, water yield and stormflow runoff peaks decrease.
- The rise or fall in water yield is proportional to the percentage area of forest added or removed (Figure 3).
- The extent of water yield changes brought about by changes in forest cover tends to increase with mean annual rainfall (Figure 4).

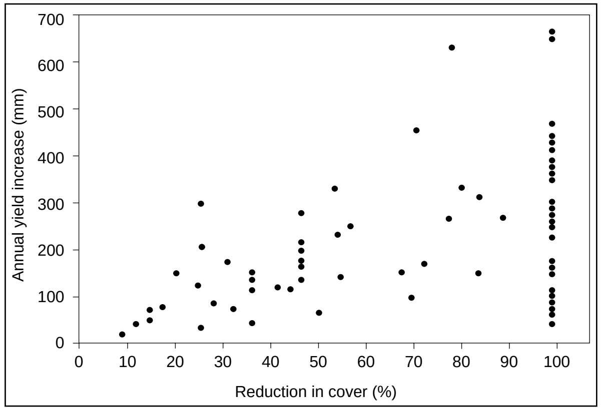


Figure 3: Relationship between reduction in forest cover and increase in water yield. (Source: Schofield 1996 and Bosch & Hewlett 1982.)

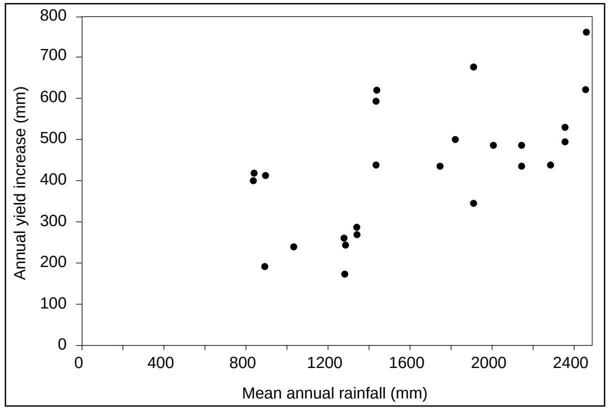


Figure 4: Water yield increases following 100% clearfelling for forest cover as a function of mean annual rainfall. (Source: Schofield 1996 and Bosch & Hewlett 1982.)

- Water yield changes are difficult to detect if less than 20% of the catchment is treated.
- Forests use more water annually than grassland (Figure 5). Grassland catchments therefore have higher runoff and increased recharge.

Apart from relying on these generalisations, it has been difficult for hydrologists to forecast the change in water yield change resulting from changes in forest cover. This is because of the complex interactions between climate, soils, vegetation and topography, which cause variable catchment behaviour.

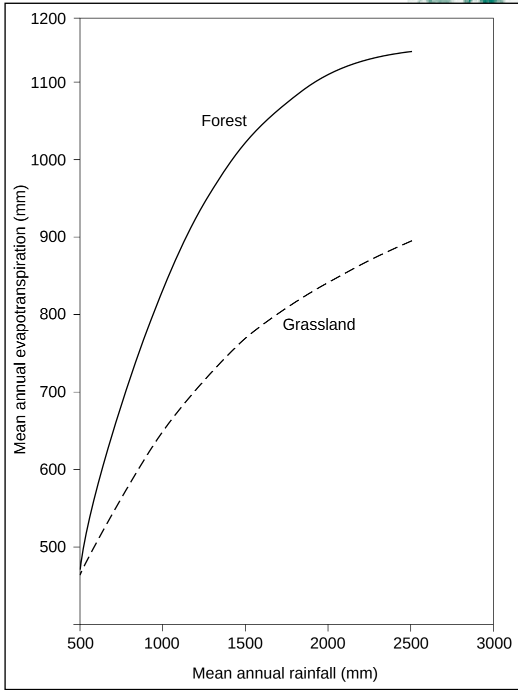
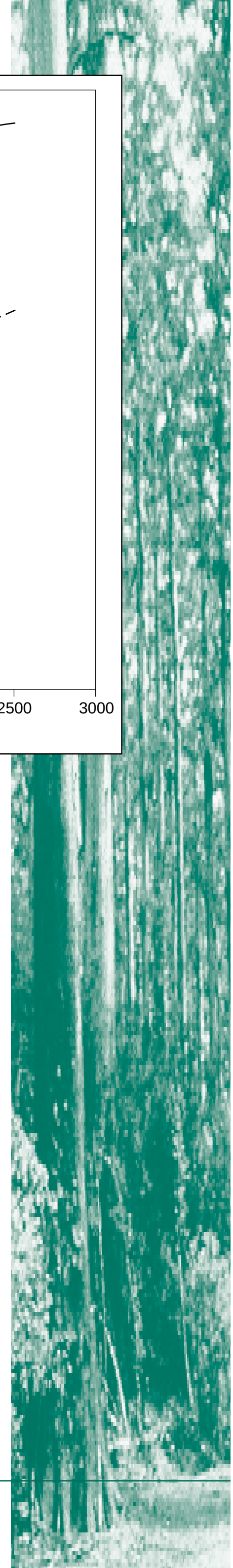


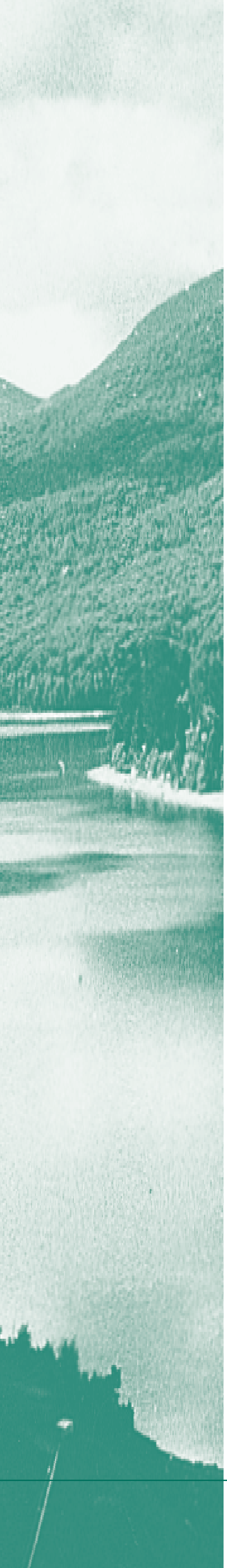
Figure 5: Mean annual evapotranspiration from pastures and forest as a function of mean annual rainfall. (This relationship was developed for 21 Victorian catchments by Holmes & Sinclair 1986.)

Catchment experiments conducted to date only cover a small percentage of the possible combinations of the above variables, and many of the long term catchment experiments are being terminated because of their high cost. Further, cost and time considerations mean that it is impractical to conduct new catchment experiments to answer new management questions. For these reasons, managers are looking increasingly to computer models to forecast the hydrologic impacts of forest change.

Project objectives

The purpose of this study was to develop an understanding of the hydro-ecology of forested catchments, that is, the interaction between forest cover and catchment water balance. This was achieved through a combination of field measurement and computer modelling.





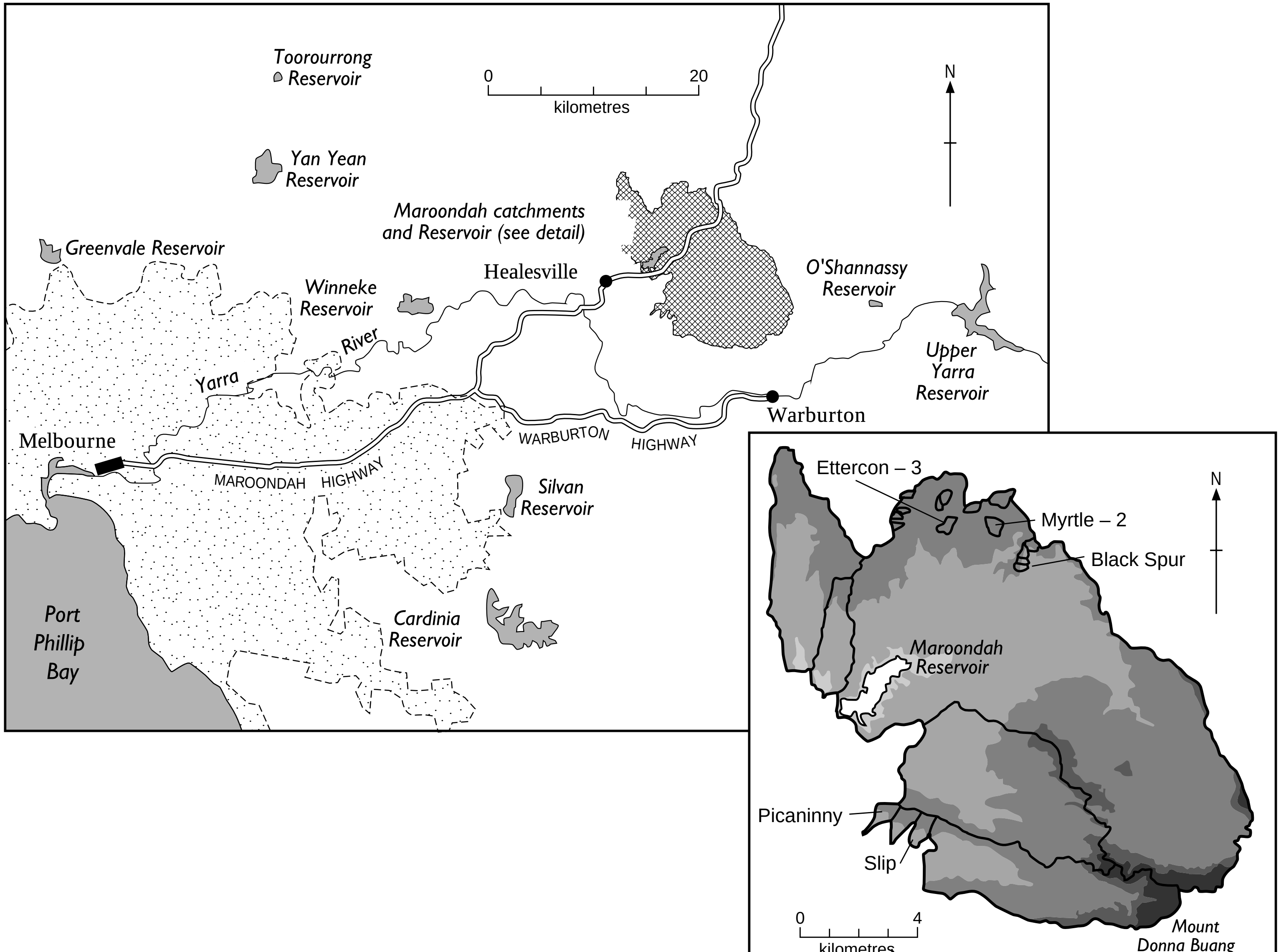


Figure 6: Location of the Maroondah catchments.

The project's specific objectives were to:

- improve our understanding of hydro-ecologic processes affecting water yield from mountain ash forest
- evaluate and improve state-of-the-art measurement techniques for measuring hydro-ecologic processes in forest ecosystems
- develop and test a physically-based catchment model suited to small experimental catchments (up to 1 km^2), which could simulate the hydro-ecologic impacts of forest disturbance
- develop and test a physically-based catchment model, suited to large water supply catchments (up to 1000 km^2), which could simulate the hydro-ecologic impacts of forest disturbance.

THE MOUNTAIN ASH FOREST

IMPORTANCE OF MOUNTAIN ASH FORESTS FOR WATER SUPPLY

In Australia, the most comprehensive program of forest hydrology experiments has been conducted in Victoria's Maroondah water supply catchments, about 60 km north-east of Melbourne (Figure 6). The catchments are typical of others in the Melbourne water supply catchment system. They are covered entirely with forest, and yield high quality water that requires minimal treatment. More than half of the forest cover is mountain ash (*Eucalyptus regnans*) which, because it is situated in the wettest areas, yields about 80% of the total runoff. Hence, mountain ash forest is of strategic importance to catchment managers.

Melbourne Water, which jointly manages the Maroondah catchments with the Department of Natural Resources and Environment, maintains a closed-catchment policy to ensure optimal water quantity and quality. Over the years, these catchment managers have been faced with considerable pressure from the timber industry to open the mountain ash forest to logging. This led to a comprehensive hydrologic monitoring program in which 17 experimental catchments were set up in the Maroondah area to determine the effects of clear-felling and selective logging on water quality and quantity (Detail plan – Figure 6).

MOUNTAIN ASH FOREST ECOLOGY

Mountain ash forests are confined to the wetter parts of the highlands of Victoria and Tasmania. In Victoria, mountain ash generally grows at altitudes of between 200 and 1000 metres, where mean annual rainfall

The Maroondah Reservoir.

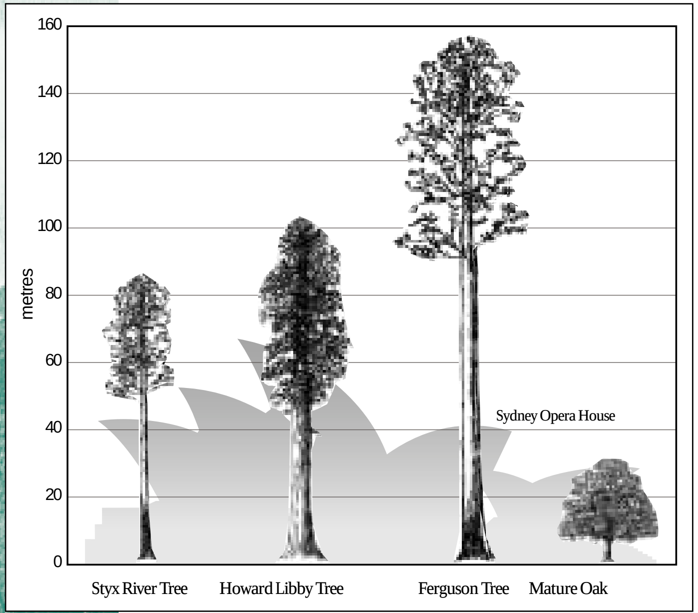


Figure 7: Some of the worlds big trees: the Styx River Tree in Tasmania, a mountain ash and Australia's tallest living tree; the Howard Libby Tree in California, a Redwood and the world's tallest living tree; the Ferguson Tree, felled in Victoria in 1872, a mountain ash and the tallest tree ever recorded.

exceeds 1200 mm. These are among the world's largest hardwood trees, attaining heights of more than 80 m at maturity (Figure 7).

Fire is a vital component of the mountain ash forest life cycle. Tree seedlings only survive and grow in exposed soil with direct sunlight. In nature, these

Wildfire is a frequent visitor to the mountain ash forest.

A forest coupe after logging and burning of slash.

Old growth mountain ash trees near the Myrtle-2 catchment, Yarra Ranges National Park.

Regrowth mountain ash forest emerging beneath remnant old growth 'stags', killed by the 1939 wildfires.

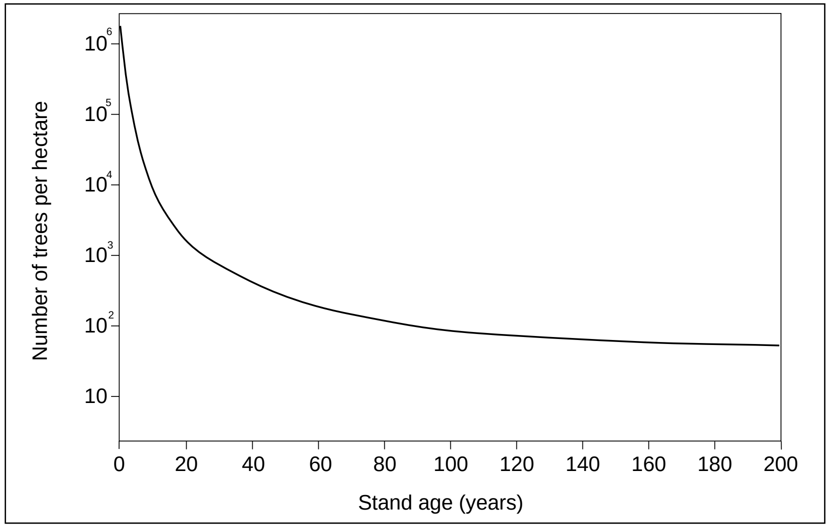


Figure 8: Relationship between mountain ash stocking rate and stand age (after Ashton 1976).

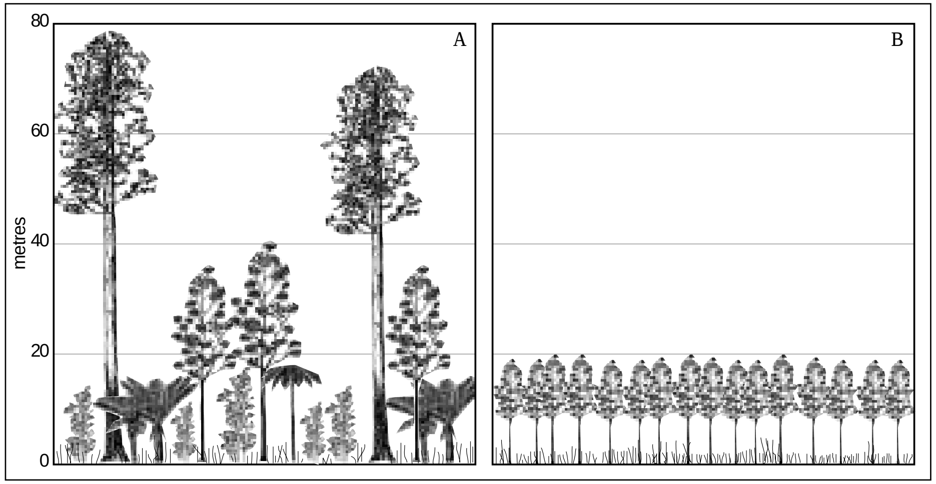


Figure 9: Comparison of forest structure in (A) old growth and (B) regrowth mountain ash stands.

conditions are only created by bushfires. Immediately after fire in a mature mountain ash forest, seed stored in woody capsules in the crowns of the trees is released onto the exposed soil surface. Hundreds of thousands of seeds germinate per hectare. The intense competition between the plants for light results in rapid tree growth in the young stand. Weaker trees are soon shaded out and die. This natural thinning of the stand proceeds quickly at first, and continues for the life of the stand at an ever-decreasing rate (Figure 8).

As the mountain ash forest thins out, gaps begin to form. Due to shading from the surrounding forest, these gaps are not filled by new mountain ash trees, but instead fill with shrubs, ferns and medium sized trees such as acacias (Figure 9). By the time the forest is more than 200 years old, tree height exceeds 80 m and gaps of up to 80 m wide have formed in the canopy. Significant understorey appears after about 15 years age, and is strongly developed by age 80 years. In the absence of fire, mountain ash would disappear from a site within 500 years.

Relationship between mountain ash forest age and water yield

Early research on mountain ash forest hydrology, conducted mainly by researchers from Melbourne Water and the University of Melbourne, showed that the amount of water yield from these forests is related to forest age (Langford 1976, Kuczera 1987). Kuczera (1985) developed an idealised curve describing the relationship between mean annual streamflow and forest age for mountain ash forest (Figure 10). The curve combines the known hydrologic responses of eight large (14–900 km^2) basins to fire, and is constructed for the hypothetical case of a pure mountain ash forest catchment. The 'Kuczera curve' is characterised by the following features:

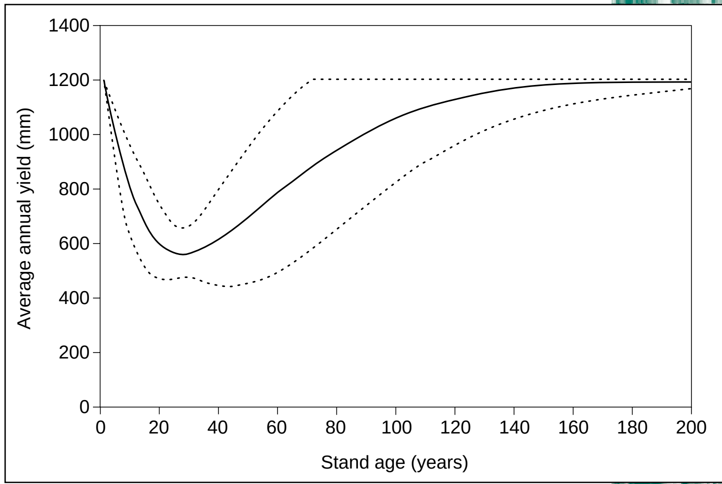
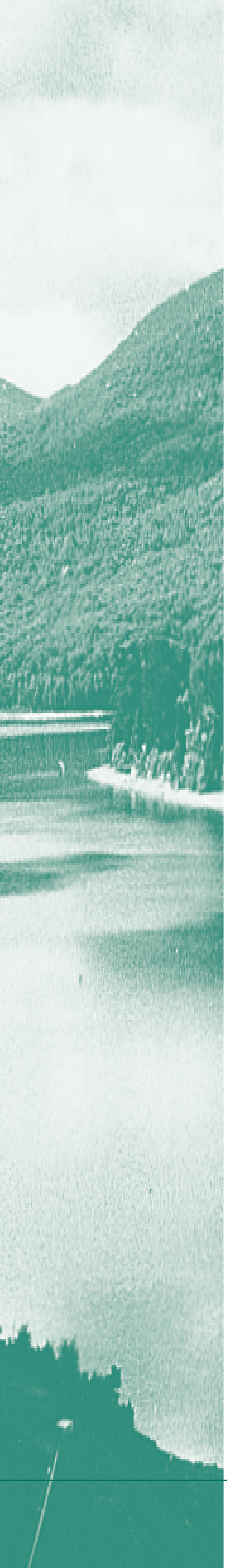


Figure 10: Relationship between mean annual runoff and stand age from mountain ash forest catchments (after Kuczera 1985). Dashed lines denote 95% confidence limits.

- The mean annual runoff from large catchments covered by pure mountain ash forest in an old growth state is about 1200 mm/y (millimetres per year).
- After burning and full regeneration of the mountain ash forest with young trees, the mean annual runoff reduces rapidly to 580 mm/y by age 27 years.
- After age 27 years, mean annual runoff slowly increases, returning to pre-disturbance levels, but taking as long as 150 years to recover fully.



While the 'Kuczera curve' is now commonly used to forecast the hydrologic impact of fire or logging in mountain ash forest catchments, it has two major limitations. First, it has wide error bands associated with it, particularly for forests aged between 50 and 120 years (Figure 10), so it is difficult to accurately predict when water yields will recover after disturbance. Second, the curve is a generalised one, masking the substantial variations that exist between ash forest catchments with different site characteristics. For instance, mean annual streamflows from individual catchments of old growth mountain ash are known to vary between 250 and 1500 mm.

Rainfall/runoff relationships at the Coranderrk catchments

We have so far discussed how runoff from large catchments has been observed to change as a function of forest age. These trends can be verified for smaller catchments by examining data from the Melbourne Water catchment treatment experiments referred to earlier.

Melbourne Water set up the Picaninny and Slip Creek catchment pair in 1955 to evaluate the water yield and quality impacts of logging mountain ash forest. At the start of the experiment, both catchments were covered with old growth mountain ash forest (about 200 years old). Early in 1972, 78% of the Picaninny catchment (0.53 km^2 area) was clearfelled and re-seeded with mountain ash. Buffer vegetation (accounting for the remaining 22% of the catchment area) was retained around the stream course. The forest in the adjacent Slip Creek catchment (0.62 km^2 area) was left in its natural old growth state. Reliable climate and streamflow data are available for both catchments from late 1968 onwards, and data is still being collected from the sites today.

The Picaninny catchment, soon after a clearfelling operation in 1972.

Mean annual rainfall for Picaninny is 1180 mm, which is fairly low for mountain ash forest. Mean annual runoff for the years 1969–1971 inclusive was 332 mm for Picaninny and 406 mm for Slip Creek. Hence, these catchments yield about one-third the annual streamflow assumed for old growth mountain ash forest by the 'Kuczera curve'.

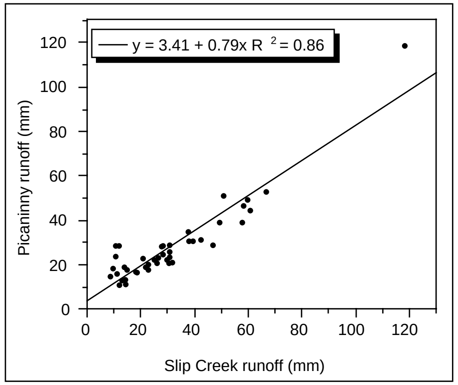


Figure 11: Relationship between monthly runoff at Slip Creek and Picaninny, two small catchments in the Coranderrk group. The data cover the period 1969–1972, when forest cover for both catchments was old growth mountain ash.

Figure 12: Annual runoff at Picaninny catchment from 1973 to 1995, expressed as the difference from expected runoff had the catchment not been disturbed.

For the three years prior to disturbance, the monthly runoff at Picaninny could be predicted from the monthly runoff at Slip Creek with 86% confidence (Figure 11). Slip Creek produces more runoff because it receives more rainfall, but otherwise the two catchments seem to behave consistently. The regression relationship shown in Figure 11 was used to estimate monthly runoff from Picaninny for the period 1973–1995 inclusive. Hence, an estimate was made of what the monthly runoff at Picaninny would have been if the forest cover was left undisturbed. This can be compared to the observed runoff from Picaninny over this same period. Figure 12 shows the annual difference between predicted and observed runoff for the Picaninny catchment.

Figure 12 shows that annual runoff increased by about 240 mm for the first two years after disturbance, reflecting the reduction in evapotranspiration that accompanies forest removal. Increases in runoff relative to the control catchment were maintained until year 7, after which a consistent reduction in runoff was evident. Between 12 and 23 years after disturbance, annual runoff from Picaninny was, on average, about 180 mm lower than expected.

The need to explain the forest stand age/water yield relationship

While the Kuczera curve and data from paired catchment treatment experiments provide a good indication of the trend in water yield response to forest disturbance, there is a need to improve predictive capacity. The main objective of this project was to build a process-based model that can predict these changes more accurately for a range of site conditions and disturbance scenarios. However, before such a model could be built and tested, it was necessary to understand what causes the water yield changes that accompany ageing of the mountain ash forest.

The forest age/water yield relationship

Leaf area index (LAI)

Leaf area index (LAI) is the amount of leaf area per unit area of ground. It tends to vary between extreme values of 0.1 and 8.0, but is usually in the range 2.0–5.0 in moist native eucalypt forests.

Leaf area index may be the key to evapotranspiration differences between mountain ash stands of different age, because LAI is known to control rates of plant transpiration and rainfall interception. It also indirectly affects soil/litter evaporation by controlling light transmission and heat flux through the canopy to the forest floor. However, prior to this work, there were no published estimates of LAI for mountain ash forests in the Maroondah area, nor any accounts of the best way to estimate LAI in these forests. Hence, we conducted a series of experiments to:

- compare different methods of estimating LAI in forests
- estimate LAI for a range of mountain ash stands of different age.

Comparing methods for estimating LAI in forests

In the first part of the study, we compared three different methods for estimating LAI in mountain ash forest. These included:

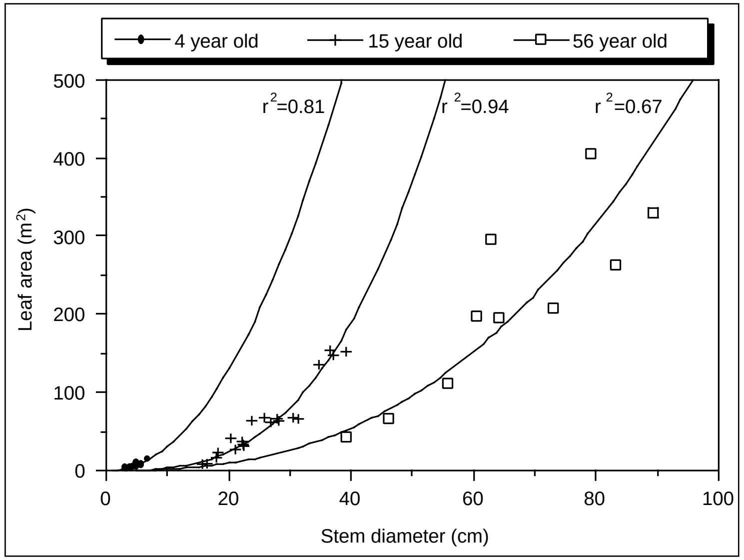
- destructive sampling
- a Plant Canopy Analyser (PCA)
- hemispherical canopy photo analysis.

Destructive sampling

Destructive sampling involves felling a sample of different sized trees and harvesting the leaves from each tree. The total leaf mass from each tree is weighed before a small sub-sample of leaves is passed through a planimeter to measure the leaf area. This same sub-sample is weighed to obtain a leaf weight to area ratio. The total leaf mass of each tree is multiplied by this ratio to estimate the tree's leaf area. The computed leaf area for that tree is

Destructive sampling of mountain ash tree canopies to determine leaf area index (LAI).

Figure 13: Relationship between stem diameter and leaf area for mountain ash trees aged 4, 15 and 56 years.



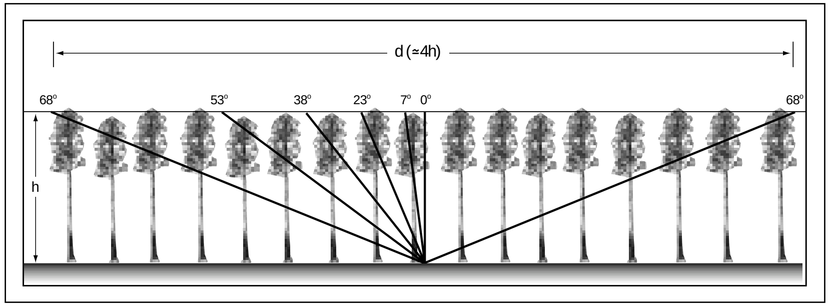
then related to the tree's stem diameter via a regression equation (Figure 13). If the stem diameter of every tree in a plot of known area is measured, the regression equation can be used to estimate the total leaf area for the plot. Finally, the LAI value for the plot is determined by dividing the total leaf area by the plot area.

Plant Canopy Analyser (PCA)

The PCA device (Licor LAI-2000) estimates LAI by comparing light readings above and below the forest canopy (see photo). In tall forests it is impractical to get above the canopy or walk out into a clearing, so two devices are used. One unit is left in a clearing to record light conditions automatically every 15 seconds. The other is used to measure light conditions beneath the canopy, with the operator walking around the site making multiple measurements. Each PCA sensor contains five separate concentric rings that detect light transmission values centred on five zenith angles (Figure 14). The sensor views a plot radius about four times the height of the vegetation. Measurements must be made in fully overcast conditions or at dawn or dusk when there is no direct sunlight on the canopy.

Measuring leaf area index (LAI) using the Plant Canopy Analyser (PCA).

Figure 14: Field of view of the LICOR LAI-2000 Plant Canopy Analyser (PCA). In our study we included data for the field between 0 and 53° only.



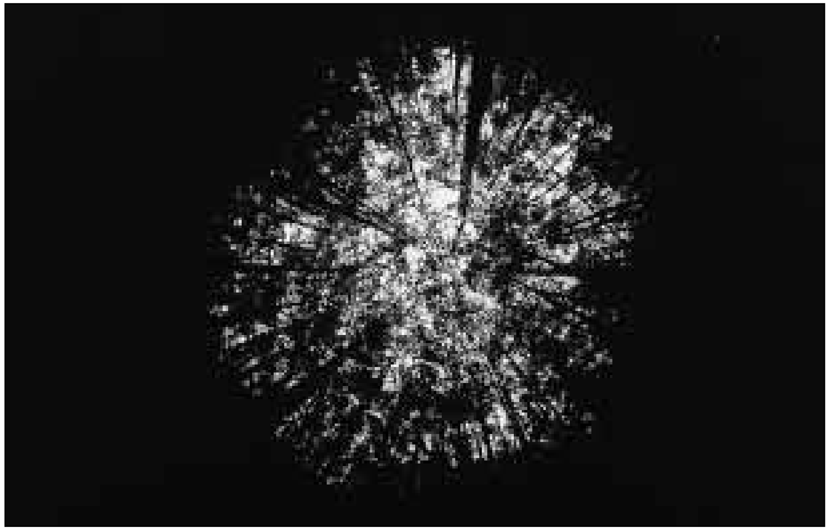
Hemispherical canopy photo analysis

Hemispherical canopy photo analysis entails taking a fish-eye photo of the forest canopy from ground level (see photo), scanning this, then analysing the digital image to compute the relative proportions of sky and canopy.

We carried out a comparison of these three methods in a 15 year old stand of mountain ash in the Monda group of catchments within the Maroondah experimental area (Table 1). The destructive sampling indicated that the plot LAI was 4.0. A range of sampling strategies was used with the PCA device, with repeated measurements being taken:

- randomly through the plot
- along transects within the plot
- at fixed positions within the plot.

Fish-eye photo of a mountain ash forest canopy, used to estimate leaf area index (LAI).



Method	Range of LAI values	Mean
Destructive sampling	–	4.0
PCA (random)	3.6–4.5	4.1
PCA (transect)	3.9–5.0	4.4
PCA (fixed position)	3.8–4.4	4.1
PCA (all measurements)	3.6–5.0	4.2
Photo	3.7–6.1	4.4

Table 1: Comparison of LAI estimates derived using different measurement methods and a variety of sampling strategies.

Method	Advantages	Disadvantages
Destructive sampling	• highly accurate • can discriminate between overstorey and understorey	• extremely labour intensive and therefore costly • damaging to the environment
PCA device	• rapid and simple measurements, allowing wide spatial coverage • no subsequent lab analysis	• instrumentation costly (~$22,000 for two units) • cannot discriminate between overstorey and understorey
Hemispherical photos	• simple to apply • relatively cheap (~$3,000 for equipment)	• cannot discriminate between overstorey and understorey • lab analysis of photo images required

Table 2: Advantages and disadvantages of various LAI estimation methods for use in mountain ash forest.

For each case, PCA estimates varied between repeated measures, but the mean value for each set of measurements ranged between 4.1 and 4.4, with an overall mean of 4.2. Different hemispherical photos yielded LAI values of between 3.7 and 6.1, with an overall mean of 4.4. Hence, all three methods yielded similar results if repeated measurements were made.

The advantages and disadvantages of the three LAI measurement methods are summarised in Table 2.

Estimating LAI for mountain ash stands of different age

In the second part of the study, we compiled a vast amount of information to determine LAI values for a range of age classes. This included historic destructive sampling data gathered by Melbourne Water in the 1980s, data from our own destructive sampling experiments, some PCA observations and a large database of stem diameter and stocking rate data.

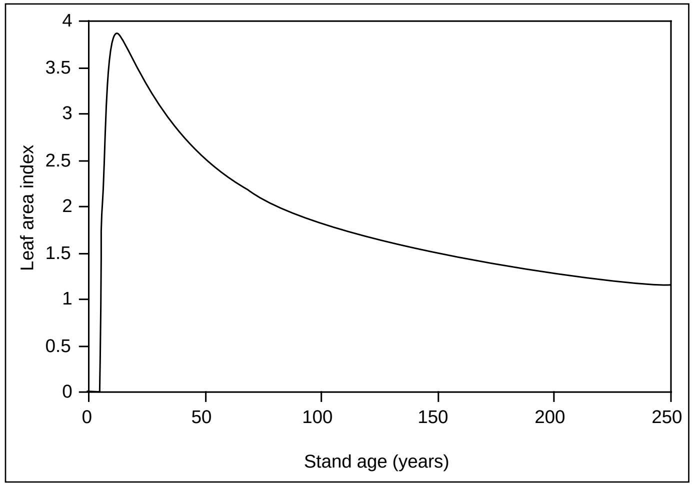


Figure 15: Relationship between mountain ash stand age and leaf area index (LAI) (after Watson & Vertessy 1996).

This information was used to expand on the kind of data illustrated in Figure 13 and to produce a generalised curve relating mountain ash stand age to LAI (Figure 15). The curve shows that LAI rises to about 4.0 at age 15 years and decreases to about 1.3 at age 235 years, resulting in about a three-fold difference in LAI between old growth and regrowth stands.

If inverted, our LAI curve has a similar shape to the 'Kuczera' curve. However, this LAI curve accounts for mountain ash (or canopy) vegetation only. Total LAI (combined mountain ash and understorey) does not vary significantly across age classes because as the mountain ash overstorey thins, more and more understorey vegetation enters the forest.

In the following section we report on how transpiration rates differ between overstorey and understorey vegetation. We also discuss how transpiration rates of overstorey trees change through time.

Transpiration by mountain ash forests

It is only recently, with the advent of the sap flow measurement technique, that we have been able to accurately measure transpiration rates in mountain ash forest. This technique uses heat as a tracer to measure the speed of water movement in the sapwood or xylem of the tree. If the sapwood area is also known, then the transpiration rate of the tree can be calculated.

We validated the sap flow method in a large mountain ash tree using a cut-tree experiment (Figure 17). A water reservoir was placed around the tree stem and filled with water. Below the water line, a deep cut was made around the circumference of the stem through the sapwood, so that all subsequent tree water uptake took place from the reservoir. Over a three

How a sap flow logger works

A sap flow logger consists of a pair of sensor probes and a data logger (Figure 16). Each sensor probe consists of a heater bar and temperature sensors embedded in bars above and below the heater. Using a jig, three 2 mm diameter holes are drilled into the tree to permit insertion of the entire sensor probe into the sapwood. The data logger is programmed to fire a pulse of heat every 20 minutes and then record the rise and fall of temperature above and below the heater. The length of time taken for the temperature sensors to respond and return to their original temperature tells us the speed of sap movement in the stem.

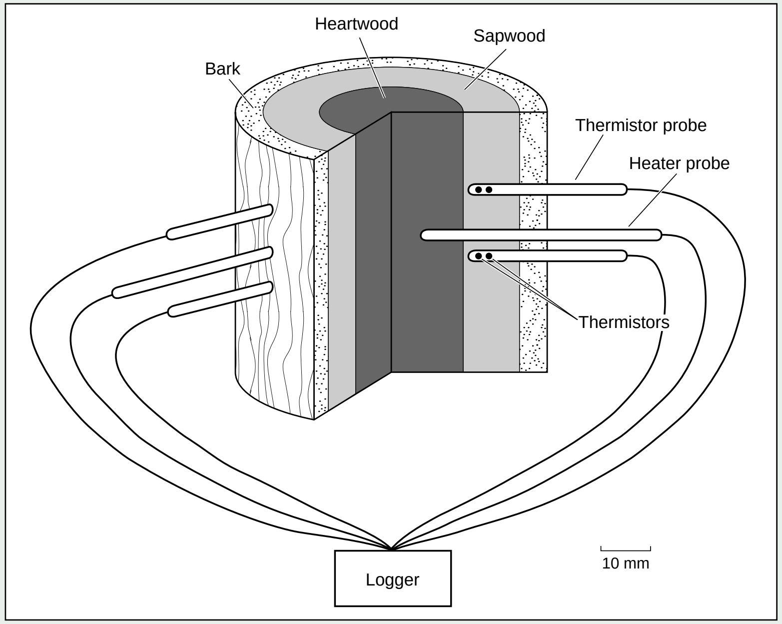
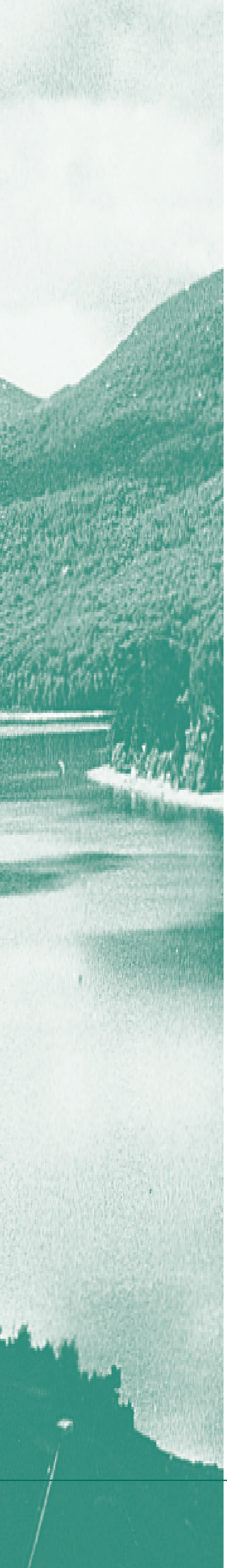


Figure 16: Diagram of a sap flow logger, including details of sensor implantation in the tree



Experimental set up to verify the sap flow method of tree water use measurements in large mountain ash trees (see also figure 17).

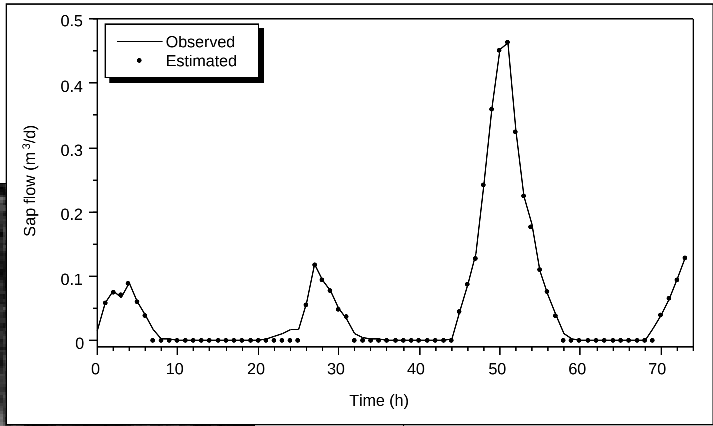


Figure 18: Observed and predicted sap flow in a large mountain ash tree (after Vertessy et al. 1997).

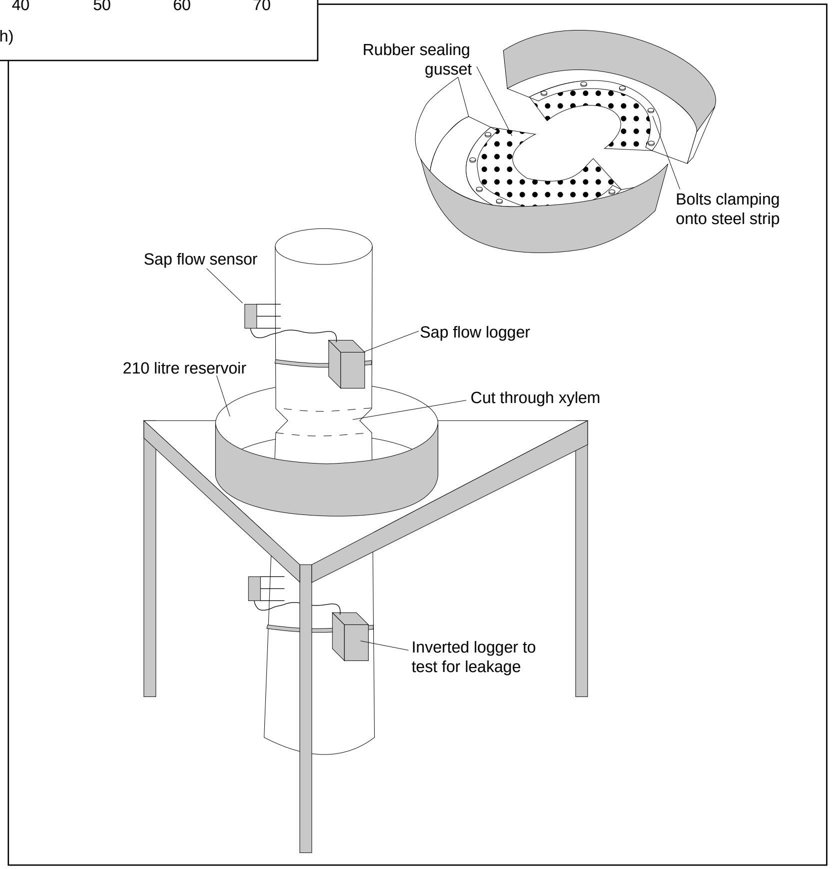


Figure 17: Details of apparatus used in the cut-tree experiment performed at Black Spur (after Vertessy et al. 1997).

day period, water uptake of the same tree was also estimated using the sap flow method and was shown to be virtually identical to the reservoir water loss (Figure 18).

The CRC and other research groups have applied the sap flow method in different-aged mountain ash stands and found that mean daily summer/spring sap velocity does not vary significantly between the stands. Across stands aged from 15 to 240 years, it ranges between 9.7 and 13.0 centimetres per hour (cm/h), with a mean of 11.6 cm/h for the six warmest months of the year. Hence, for each square metre of sapwood, we can assume a sap flow of 496 m^3 for those six months. Assuming that sap flow for the other six (cooler) months of the year would be lower in proportion to the lower potential evapotranspiration rate during that time, we can assume that the sap flow for the other six months is 224 m^3. Combining these two estimates gives an annual sap flow rate of 720 m^3/m^2 of sapwood area.

Transpiration by understorey vegetation

Earlier, we noted that total LAI in the mountain ash forest does not change significantly over time, but the partitioning of LAI into overstorey and understorey components does. We have observed that understorey LAI can increase from about 0.1 in a 6 year old forest to about 3.0 in an old growth forest. Hence, in the later stages of the life of a mountain ash forest, the understorey can be an important component of the forest water balance. However, it is unlikely that overstorey and understorey trees transpire at the same rate, so measurements of understorey transpiration also had to be made.

Using the sap flow method, we conducted experiments to measure understorey transpiration and to test the hypothesis that understorey trees might use less water (per unit leaf area) than overstorey trees. We selected a site in 1939 regrowth forest that had a mountain ash overstorey with an LAI of 2.4, and an understorey of hazel (*Pomaderris aspera*) with an LAI of 2.6. We installed sap flow loggers in 6 mountain ash trees and 10 hazel trees of different size, and measured their water use over one month. The results in

How much water does a large mountain ash tree use?

Large old growth mountain ash trees can use as much as 800 litres of water per day and consume more than 100,000 litres over a full year. However, because the spacing between old growth trees is so large (the stocking rate is typically less than 50 trees per hectare), the total water use of of an old growth stand is not as great as for a stand with smaller, younger and more densely spaced trees. Figure 19 shows a typical daily water use pattern of a large tree over two days in summer.

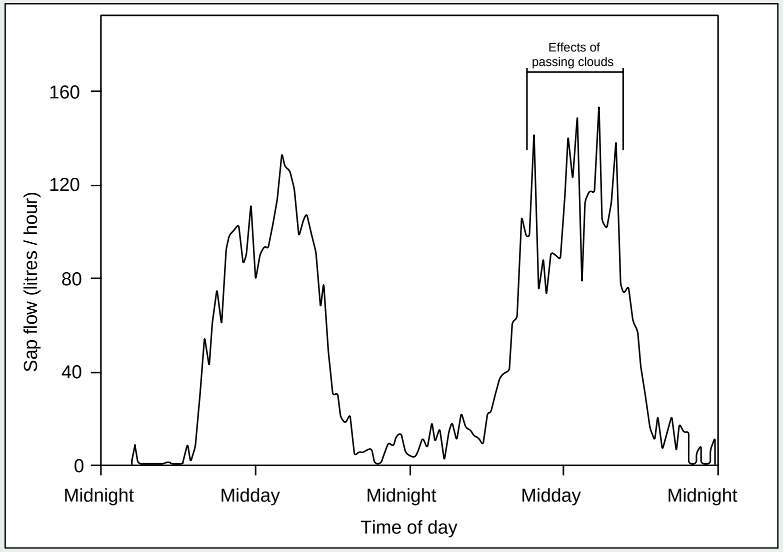


Figure 19: Hourly values of sap flow in a large mountain ash tree over a two day period in summer.

	Overstorey (mountain ash)	Understorey (hazel)
Number of trees	6	10
Leaf area of all trees (m^2)	597	242
Sapflow of all trees (litres/day)	566	146
Leaf area/sapflow ratio (litres/day/m^2)	0.95	0.60

Table 3: Comparison of leaf area and sap flow rates in overstorey and understorey trees in a 1939 regrowth mountain ash forest.

Table 3 indicate that understorey trees transpire significantly less on a per unit leaf area basis than overstorey trees.

The reasons for this difference may be that understorey trees receive less radiation due to shading, and experience less wind turbulence and more humidity. Support for this hypothesis comes from another study we conducted comparing the water use behaviour of overstorey and understorey trees over a range of climate conditions (Figure 20). During a 39-day sampling period in spring, we found that the differences in transpiration rate between overstorey and understorey trees were greatest on cloudy or still days when the canopy would have captured most of the radiation, and eliminated the movement of air currents down to the understorey.

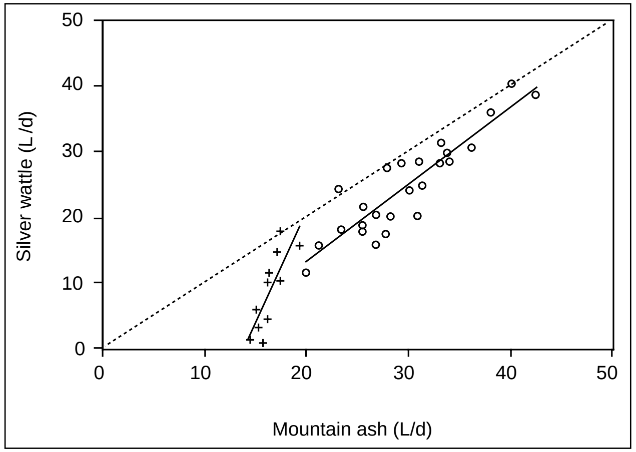


Figure 20: Comparison of daily water use (litres per day) by a mountain ash (overstorey) and silver wattle (understorey) tree (after Vertessy et al. 1995).

Sapwood area

Earlier, we discussed how sap velocity does not differ significantly between different-aged mountain ash stands. This simplifies the estimation of tree water use rates, as we would only need to find how sapwood area changes with forest age.

By coring many trees in a number of stands and collating the large amount of existing data on sapwood area in mountain ash, we were able to construct a picture of how sapwood area changes over time in these forests. Expressed on a sapwood area per unit ground area basis, we found that sapwood area rises to about 10.6 square metres per hectare (m^2/ha) at age 15 years, then declines to about 3.6 m^2/ha at age 240 years (Figure 21). Because sap velocity can be assumed constant across age classes, this three-fold difference in sapwood area for the mountain ash overstorey translates into a three-fold difference in transpiration for that part of the forest.

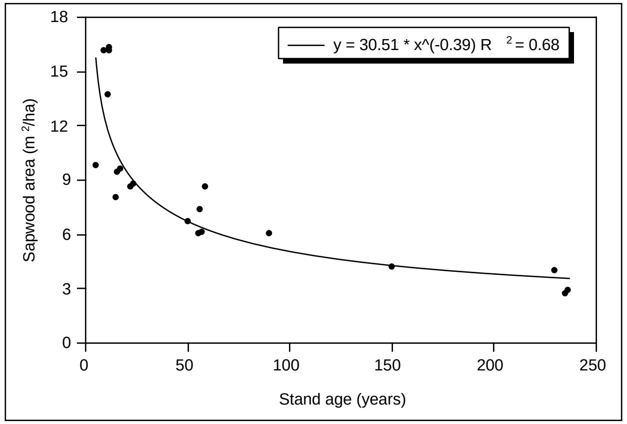
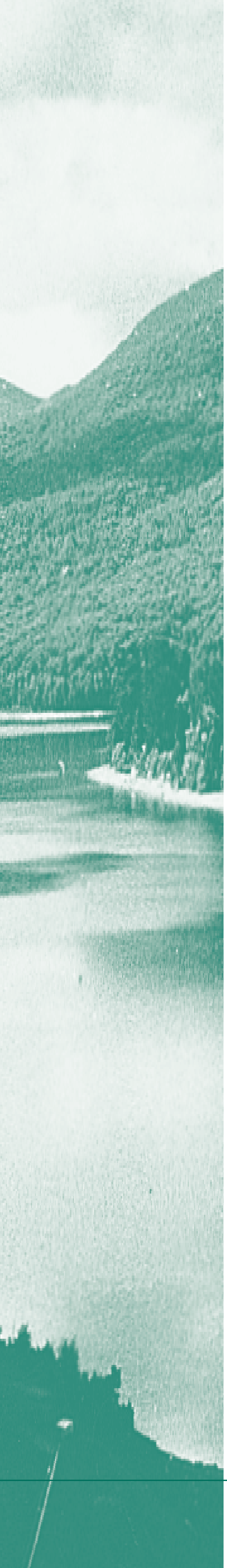


Figure 21: Relationship between mountain ash sapwood area (square metres per hectare) and stand age (years).



Soil/litter evaporation (Es)

So far, we have spoken about transpiration from tree leaves. Some water is also lost from the forest by direct evaporation from soil and litter. Soil/litter evaporation (Es) from the forest floor has received little attention in the literature, and many published estimates of forest evapotranspiration ignore Es on the assumption it is negligible. However, those studies that have considered Es from the forest floor have shown it can be a significant component of the catchment water balance. We conducted a two-part study to determine:

- how different Es measurement methods compare
- how Es contributes to evapotranspiration in different-aged mountain ash forest.

How Es measurement methods compare

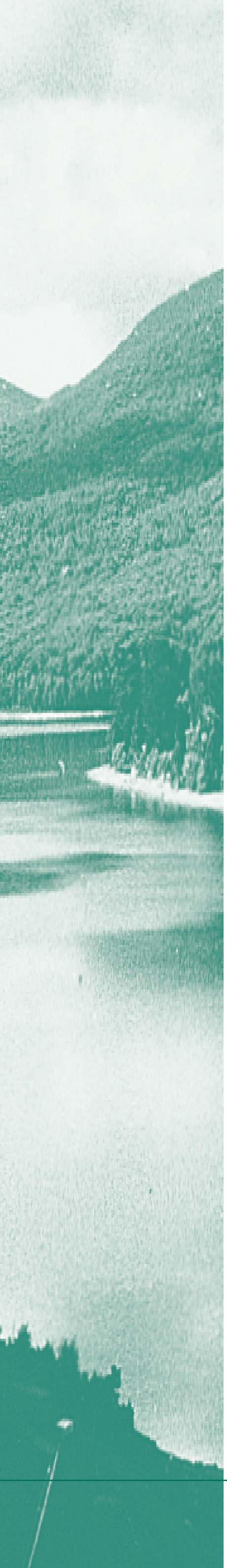
In the first part of the study, we measured Es over four days in a fallow field near Wagga Wagga, NSW, using microlysimeters and a humidity dome.

Microlysimeters are small plastic tubes (in this case, 140 mm long and 85 mm wide) which are filled with soil, topped with litter, and lowered into a sleeve inserted into the ground (see photo). Every hour or day, depending on the period of interest, the microlysimeter is extracted from the sleeve and weighed. The difference in weight between readings indicates how much moisture has evaporated from the core.

A humidity dome is a transparent plexiglass dome (1120 mm wide and 350 mm high) fitted with air circulation fans and a humidity and temperature probe inside the dome (see photo). A measurement is taken by lowering the dome onto the ground surface, ventilating the air within the dome using the fans, and recording the change in temperature and humidity at 1 second intervals for about 10–15 seconds. The rate of change in temperature and

Microlysimeter and access sleeve, used for measuring soil and litter evaporation.

The humidity dome method for measuring soil and litter evaporation.



humidity is fairly linear for the first few seconds, then decreases as the air inside the dome becomes more humid. The initial rate of change is related to Es.

Results from each of the four days of measurement given in Table 4 indicate that the two methods compare closely, in a fallow field situation.

Day	Es Microlysimeters	Es Humidity dome
1	0.5	0.4
2	0.4	0.6
3	1.0	1.0
4	0.3	0.4
Total	2.2	2.4

Table 4: Comparison of daily Es estimates (in mm) for a fallow field, determined using microlysimeters and a humidity dome (after McJannet et al. 1994).

How Es contributes to evapotranspiration in different-aged mountain ash forest

In the second part of the study, microlysimeters were used to estimate daily values of Es on five days beneath regrowth (11 year old) and old growth (235 year old) forest. The key differences between these two sites were vegetation height and density (see Figure 9, page 7). In the 11 year old stand, the mountain ash trees were 15 m tall and very closely spaced (2625 trees per hectare) with very little understorey vegetation. In the 235 year old stand, the mountain ash trees were 80 m tall and widely spaced (50 trees per hectare), and there was a well developed understorey. Figure 22 shows that Es was similar at the two sites on three days, but was much larger in the young forest on the other two days. This suggests that Es beneath mountain ash forest is influenced by forest age, the mean daily Es rate being 0.36 millimetres per day (mm/d) for the 11 year old stand and 0.28 mm/d for the 235 year old stand.

Using these figures, we have estimated that soil/litter evaporation accounts for about 10–11% of annual evapotranspiration in mountain ash forest.

For three of the five measurement days, Es was also measured using the humidity dome. These estimates are listed in brackets in Figure 22. On all three days, and at both sites, the humidity dome registered readings of Es typically 3–4 times higher than determined using the microlysimeters. Although the two methods compared favourably in the earlier fallow field trail, we believe that there are reasons why the humidity dome should overestimate Es in forest floor situations. In forests with thick litter layers, Es is heavily damped and takes place only in association with short, sharp gusts of wind that make it down to the forest floor. This is not the case in fallow fields where the soil surface is well ventilated. We concluded that, in the forest floor situation, the ventilation within the dome (created by the

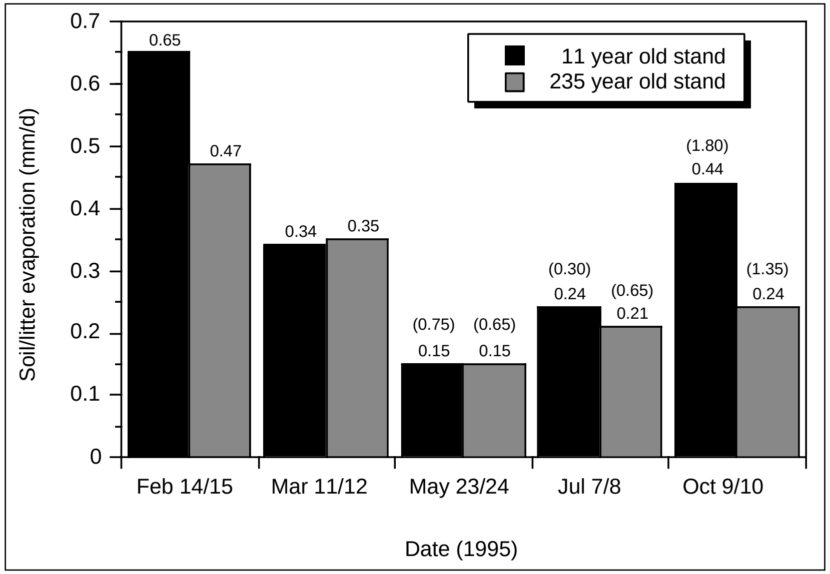


Figure 22: Comparison of soil/litter evaporation estimates beneath 11 and 235 year old mountain ash forest stands, obtained using the microlysimeter method. Values in brackets are humidity dome estimates.

fans) was too great and too continuous, resulting in a large overestimate of Es. We recommend adaptation of the humidity dome so that the ventilation rate inside the dome is matched to the windspeed immediately above.

The advantages and disadvantages of microlysimeters and humidity domes for Es determination in forests are summarised in Table 5. Clearly, neither method is ideal, but for use in forest water balance studies, microlysimeters are the better option.

Method	Advantages	Disadvantages
Microlysimeters	• very cheap and simple to build • robust • can be checked daily	• very labour intensive • integrates over a small area, requiring many replicates • soil in cores must be replenished every few days • data logging not possible
Humidity dome	• relatively cheap (~$3,000) • simple to use • integrates over a large area, requiring fewer replicates • can be moved between sites quickly • data logging is possible	• relatively untested • may over-ventilate and hence overestimate Es • integrates over a very short time, requiring many measurements for a daily total • labour intensive

Table 5: Advantages and disadvantages of microlysimeters and humidity domes for estimation of Es in forests.

Rainfall interception

Rainfall interception is the fraction of gross rainfall caught by the forest canopy and evaporated back to the atmosphere. It is estimated by subtracting measurements of rainfall under the canopy (throughfall) and water running down tree stems (stemflow) from gross rainfall measurements, collected in a

Throughfall measurement troughs beneath regrowth mountain ash trees, Picaninny catchment.

Measuring stemflow in the Picaninny catchment.

clearing or above the canopy. Previous studies have indicated that the forest intercepts as much as 30% of gross rainfall, and that there is no apparent trend between rainfall interception rate and forest age.

Our latest findings, however, indicate that stand age *does* have an impact on the rainfall interception rate in mountain ash forests. There is significant

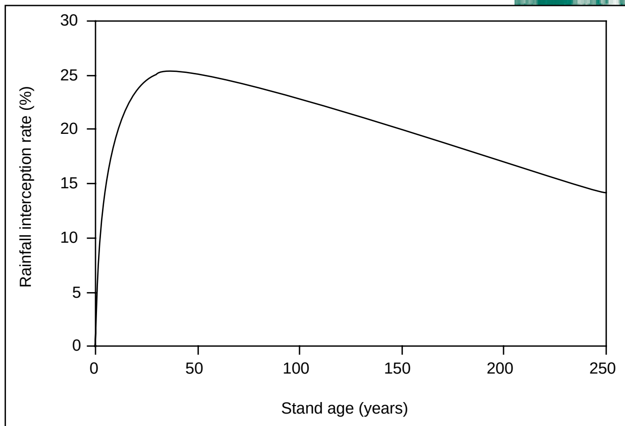
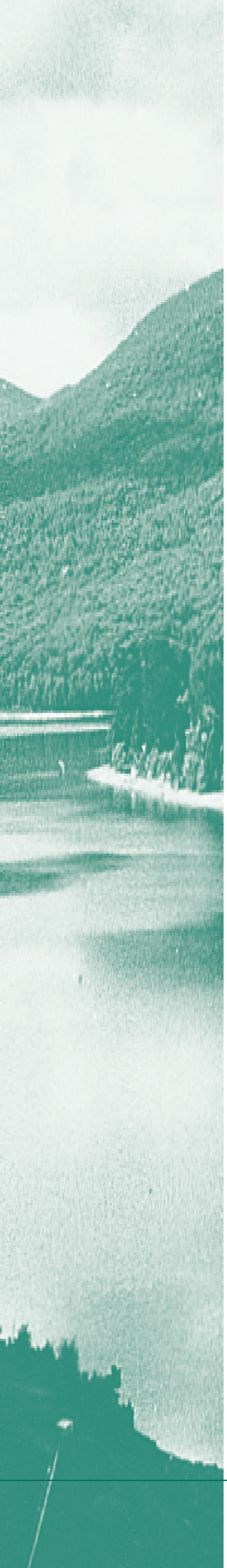


Figure 23: Relationship between mountain ash rainfall interception rate and stand age (after Haydon et al. 1996).



'noise' in the relationship but the trend line through the data can be used as a predictive tool. This trend line (Figure 23) indicates that the rainfall interception rate rises to a peak of 25% at age 30 years, then declines slowly to about 15% by age 235 years. If we assume a mean annual rainfall of 1800 mm for the mountain ash forest, stands aged 30 years intercept 190 mm more rainfall than old growth forest aged 240 years.

Parameter	How estimated	Stand age (years)				
		15	30	60	120	240
Overstorey LAI	Fig. 15	3.8	3.1	2.3	1.7	1.2
Understorey LAI	(1)	0.4	1.1	1.8	2.3	2.4
Total LAI		4.2	4.2	4.1	4.0	3.6
Overstorey sapwood area (m^2/ha)	Fig. 21	10.6	8.1	6.2	4.7	3.6
Overstorey transpiration (mm)	Fig. 21 (2)	760	580	440	340	260
Understorey transpiration (mm)	Table 3 (3)	50	130	220	290	300
Rainfall interception (mm)	Fig. 23 (4)	400	450	440	370	260
Soil/litter evaporation (mm)	Fig. 22 (5)	130	120	120	110	100
Total evapotranspiration (mm)		1340	1280	1220	1110	920
Runoff (mm)	(6)	460	520	580	690	880

Notes: (1) Estimated by subtracting overstorey LAI from total LAI, assumed to decline linearly from 4.2 to 3.6 between 15 and 240 years. (2) Combines Fig. 21 with the Dunn and Connor (1993) annual sap flow estimate of 720 m^3 transpired per m^2 sapwood area. (3) Scaled from mean overstorey transpiration rate (200 mm per year per unit LAI), assuming 126 mm per year (200 mm x 0.63) per unit understorey LAI. (4) Based on Equation 2 in Haydon et al. (1996), but accounting for stemflow. (5) Linearly interpolated between the mean daily average soil/litter evaporation rate for the 11 and 235 year old stands. (6) Does not account for moisture storage effects, important in the early stages of forest growth.

Table 6: Water balance quantity estimates for five different age classes of mountain ash forest. (An annual rainfall of 1800 mm is assumed, and each estimate is rounded to the nearest 10 mm.)

A PRELIMINARY WATER BALANCE

Given what we now know about the effect of stand age on water balance parameters in the mountain ash forest, we can estimate a preliminary water balance for stands of different age (Table 6).

Each of the estimated water balance components is depicted in Figure 24 and can be summarised as follows:

- annual overstorey transpiration declines from 760 mm at age 15 years to 260 mm at age 240 years
- annual understorey transpiration increases from 50 mm at age 15 years to 300 mm at age 240 years, off-setting (by half) the reduction in over-storey transpiration over the same period

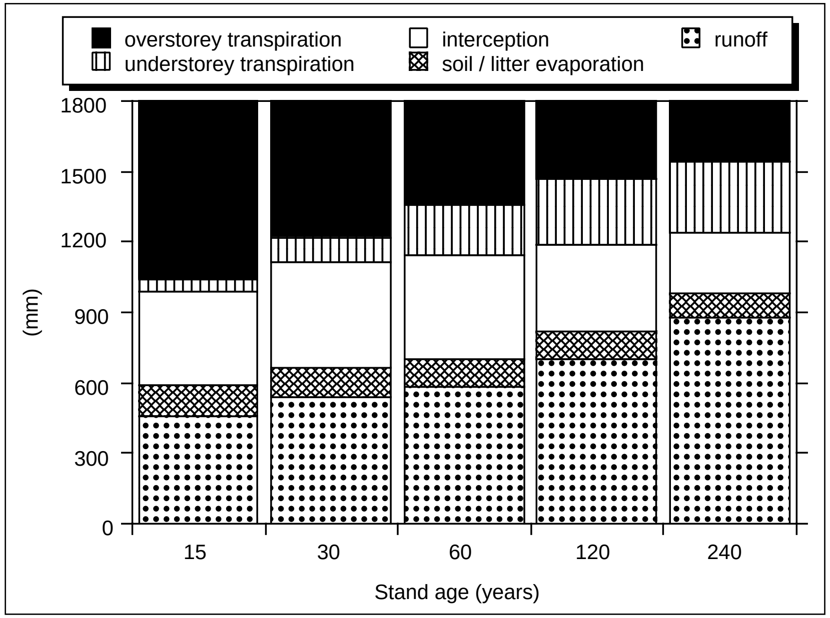


Figure 24: Water balance for mountain ash forest stands of various ages, assuming annual rainfall of 1800 mm.

- annual rainfall interception peaks at 450 mm at age 30 years and declines to 260 mm at age 240 years, further reducing evapotranspiration
- overall, there is a 420 mm difference in the annual evapotranspiration of 15 and 240 year old forest, which results in a runoff difference of the same magnitude
- 48% of the change in runoff is attributable to differences in transpiration, 45% is due to rainfall interception differences, and 7% is due to changes in soil/litter evaporation.

This simple water balance cannot necessarily be applied to the entire mountain ash forest resource. As we move away from the climate regime in which our field measurements were based, we would expect to see different values for sapwood and leaf area, as well as changed energy inputs. These would all have an effect on evapotranspiration. Our strategy has been to develop sound relationships between these variables at one site, and use hydrologic models to modulate these relationships for other settings in the mountain ash forest.

SMALL SCALE CATCHMENT MODELLING

In this project, we developed and tested a small scale catchment model called Topog. Topog is a physically based catchment model that simulates interactions between soil water, groundwater, canopy microclimate, plant growth and catchment topography (Figure 25). It runs on a daily time-step, and is driven by time-series inputs of daily rainfall, total daily solar radiation, mean daily temperature and humidity. It predicts soil moisture distribution, transpiration and rainfall interception for both the overstorey and understorey vegetation, daily evaporation from the soil/litter layer and streamflow. The model also predicts forest growth, represented as changes in leaf, stem and root biomass of both understorey and overstorey vegetation.

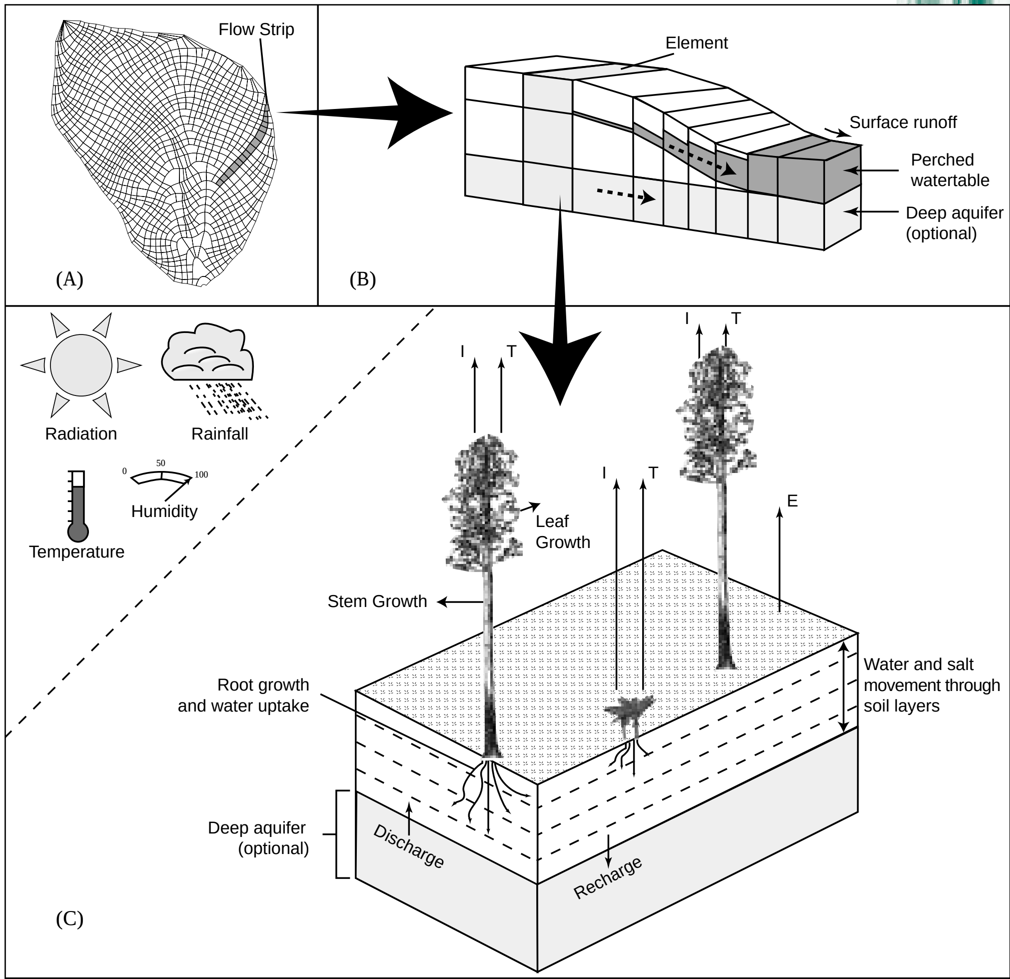
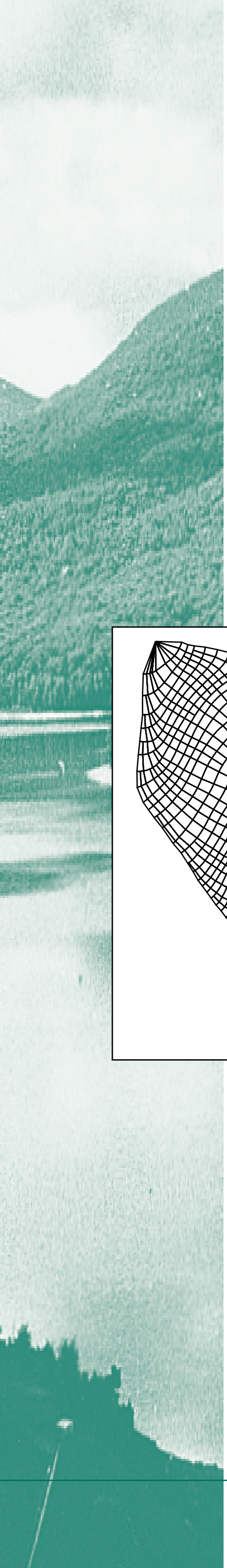


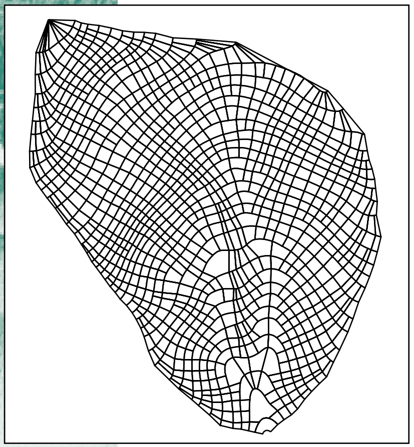
Figure 25: Hydrologic processes simulated by the Topog catchment model: (a) the full element network, (b) a single flow strip, and (c) a single element. I = evaporation of intercepted rainfall, T = plant transpiration, and E = soil/litter evaporation.

Topog uses a flow net defined by elevation contours and lines of steepest slope (Figure 26), which has been proven to be better than conventional rectangular



Topog Online: A Web resource for Topog modellers

As part of this project, we established a World Wide Web site called *Topog Online* for potential users to access the Topog model. The site can be found at http://www.clw.csiro.au/topog. As well as accessing the model code, visitors to the site can learn about the model, download data files and references describing Topog applications, notify us of bugs in the program code, and register for forthcoming user workshops. A comprehensive user manual can also be accessed and there are a series of graphical images of model output to give users a quick grasp of what the model can simulate.



flow nets. It includes an automated terrain analysis system that builds the flow net from a contour map and calculates terrain attributes (such as slope and aspect) for each flow net element. Spatially variable catchment properties can be ascribed to specific elements in the flow net.

Figure 26: Topog element network for the Myrtle-2 catchment.

Testing Topog at the Myrtle-2 catchment

Topog was applied to the 0.32 km^2 Myrtle-2 catchment (Figure 26). The observed and predicted daily runoff values for the site were compared for a continuous 12 year period (1972–1983) when the catchment vegetation was in an old growth state. All input parameter values were based on published or measured data, although some variables were adjusted within the range of known variability to yield a best fit between predicted and observed streamflow in the first year of simulation, 1972. The model was ‘calibrated’ for the first year, but all variables other than climatic inputs remained fixed for the following 11 years.

Modelled and observed daily runoff values compared well throughout the period of simulation, despite a wide range of climatic conditions. Specifically:

- the model explained 87% of the variation in observed monthly stream-flows over the 12 year period (Figure 27)
- modelled annual runoff was within ±5% of observed values for 6 of the 12 years of record
- annual runoff prediction errors exceeded ±10% of observed values in only 2 of the 12 years
- by the end of the 12 year simulation, the model had over-predicted runoff by less than 5%.

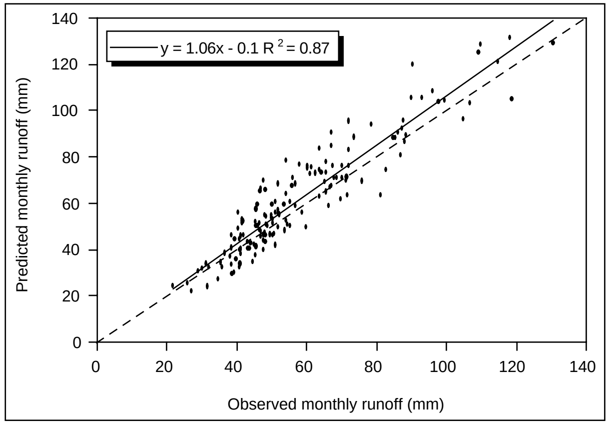


Figure 27: Comparison of Topog predictions of monthly runoff for the Myrtle-2 catchment and field observations (after Vertessy et al. 1993).

This was the first test of Topog's ability to simulate long term water yield from a forest catchment. The test indicated the model could produce stable and reasonably accurate flow predictions for mountain ash forest catchments. However, a critical factor in these simulations was that vegetation status was fixed as old growth and did not change with time. This was appropriate for the Myrtle-2 case, but for cases where the forest is recovering from disturbance, dynamic changes in forest cover need to be represented by the model.

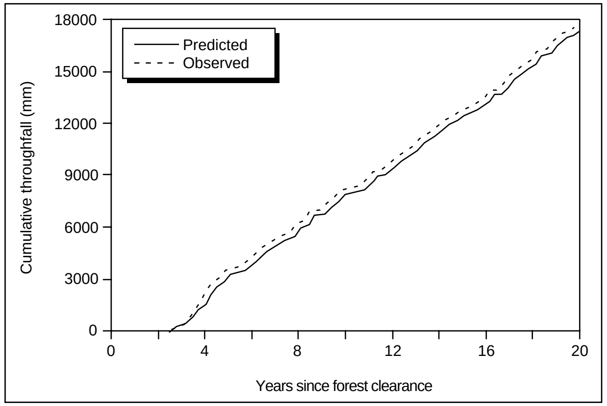


Figure 28: Comparison of Topog predictions of cumulative throughfall at the Picaninny catchment and field observations (after Vertessy et al. 1996).

Testing Topog at the Picaninny catchment

To test Topog's ability to cope with dynamically growing vegetation, the model was applied to the 0.53 km^2 Picaninny catchment. The simulation period included a 3 year pre-treatment phase when vegetation was in an old growth state, and a 20 year post-treatment phase in which the vegetation was continually changing. As in the Myrtle-2 application, model performance was evaluated by comparing observed and predicted streamflows. However, in the Picaninny application, other components of the model were also tested, using rainfall interception, soil moisture content and tree growth data obtained from the field. In the Picaninny application, the following results were obtained:

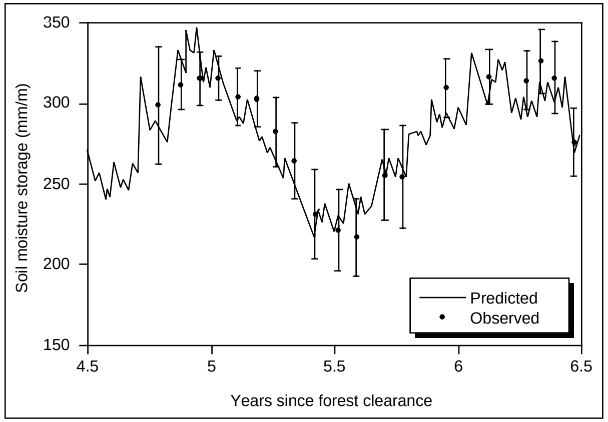


Figure 29: Comparison of Topog predictions of soil moisture storage at the Picaninny catchment and field observations (after Vertessy et al. 1996).

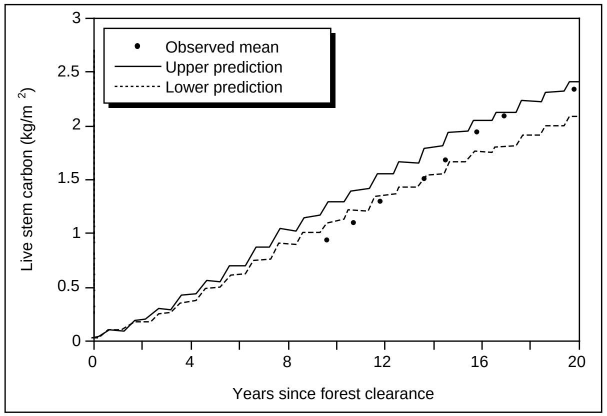


Figure 30: Comparison of Topog predictions of live stem carbon gain at the Picaninny catchment and field observations (after Vertessy et al. 1996).

- cumulative throughfall (gross rainfall less interception) was predicted within 1% of the observed value over an 18 year period (Figure 28)
- over a 4 year period, predicted soil moisture storage in the upper 1.5 m of soil agreed well with field observations (Figure 29)
- the model did a good job of predicting stem and leaf biomass for both understorey and overstorey vegetation (Figure 30)
- there was good correspondence between observed and predicted daily

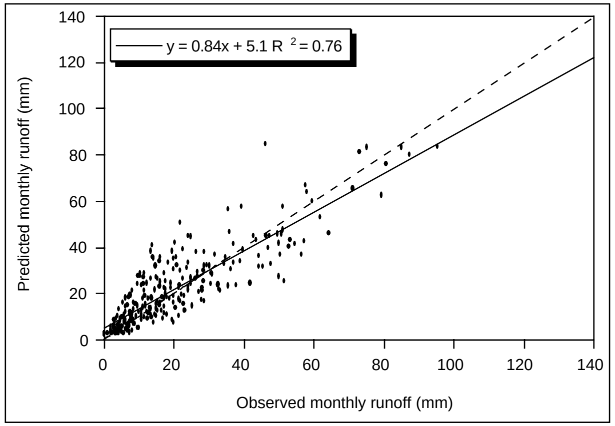


Figure 31: Comparison of Topog predictions of monthly runoff at the Picaninny catchment and field observations (after Vertessy et al. 1996).

streamflows, and the model was able to explain 76% of the variation in monthly flows (Figure 31)

- over the 23 year simulation period, the model over-predicted cumulative streamflow by only 6%.

To our knowledge, the Picaninny application of Topog is the only published account of a physically based hydrologic model being used to model dynamic forest growth and catchment water balance for a long time sequence. Part of the reason for the good fit between model results and field observations was that the model was 'tuned' using the observed data. Most of the input parameter values were measured for the site or taken from the literature, but several were used as 'calibration parameters'. These gave us some flexibility in matching model outputs with field observations. However, now that an input parameter set has been developed, it can be used for a range of catchments in the mountain ash forest setting, as well as to simulate the impact of different logging treatments and climate change.

Feeding data to the Topog model

An assessment of any model is not complete without some discussion about model parameter problems. Models like Topog are often referred to as 'parameter hungry' because they require large input data sets on catchment soil, vegetation, climate and topographic properties. Clearly, model results will only be as credible as the input data used.

For our mountain ash forest modelling, we found that reasonable quality topographic, vegetation and climate data were readily available or relatively simple to measure ourselves. This is because good field measurement techniques existed to gather such data quickly, and because these properties do not vary greatly across catchments. However, obtaining suitable soil data was a problem. Models such as Topog require information on soil depth, porosity and saturated hydraulic conductivity (Ks). These properties do vary substantially across catchments, and are difficult to measure accurately. In the following section, we refer to the special problems we faced in determining Ks values for our study sites.

Measuring saturated hydraulic conductivity (Ks)

Saturated hydraulic conductivity (Ks) is one of the most variable and difficult catchment properties to measure. It defines the maximum rate of water movement in soils, and is therefore one of the most sensitive parameters to change in physically based catchment hydrologic models. Ks is affected by soil porosity, pore size distribution and pore continuity, as well as by macropores created by root and worm channels.

At the beginning of our study, we decided to address three key questions:

- What is the best way to measure Ks in a forest soil?
- How does Ks vary spatially across a typical forest catchment?
- How important is Ks accuracy for a catchment simulation?

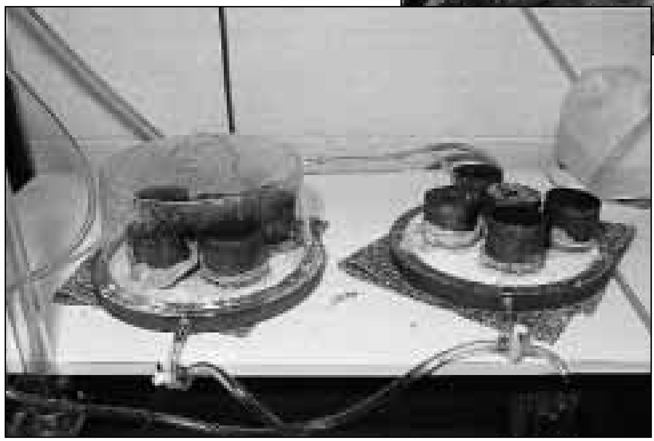
What is the best way to measure Ks in a forest soil?

A range of methods exists to determine Ks in field soils. These vary greatly in terms of implementation effort and accuracy, and tend to produce different results when applied to a given soil.

The most popular lab-based method is based on collection of undisturbed small cores (less than 10 cm diameter); in the laboratory these are placed in a constant head device to determine Ks. This technique suffers from at least two major problems: first, it is common for edge effects to dominate the Ks estimate; and second, cores of this size rarely contain any major structural features such as macropores, which significantly affect Ks. Researchers have sought to overcome these problems by basing Ks measurements on much larger cores or monoliths. However, a major logistic effort is required to work with large cores or monoliths, and some major problems with the method still exist.

The borehole permeameter method is by far the most popular field-based method of determining soil Ks. This involves augering a hole of about 5 cm diameter and maintaining a constant head of water in the hole until the

Large pit, excavated to obtain small cores for Ks measurements at the Black Spur site.

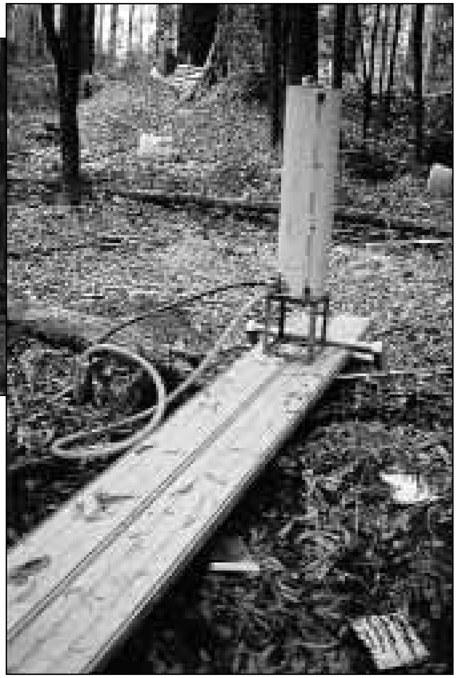


Laboratory apparatus used to determine the hydraulic properties of small cores.

Excavator assisted retrieval of large cores from the Black Spur site.

Laboratory apparatus used to determine the Ks of large cores.

Augering holes for insertion of the borehole permeameter.



Field measurement of Ks using the borehole permeameter method.

water outflow rate from the hole is steady. The attraction of the technique is that it is simple and quick to apply, particularly at depth. Further, it integrates over a larger soil area than small cores, so structural features are more likely to be represented.

We compared three sets of Ks estimates for the Black Spur site (See Figure 6, page 4), each set obtained using a different measurement technique. The borehole permeameter (BP), small core (SC) and large core (LC) methods were all applied within a plot measuring 50 x 50 m.

As anticipated, each of the measurement methods produced different Ks estimates for various depths through the soil profile (Figure 32). Median Ks values for the upper soil layer (0–50 cm) varied between 5.5 metres per day (m/d) for the LC method, 0.35 m/d for the SC method and 1.8 m/d for the BP method. Differences between the methods for layer 2 (50–500 cm) were

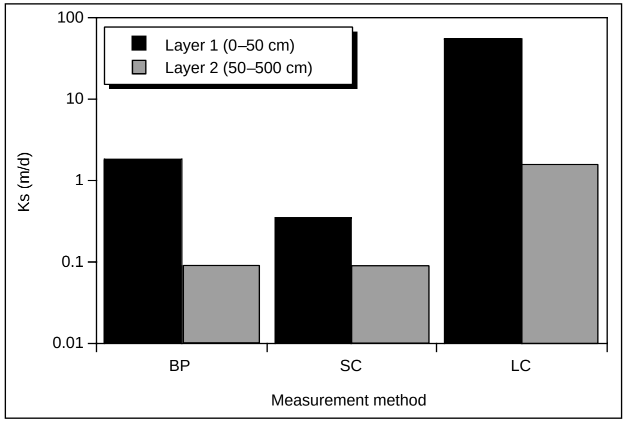


Figure 32: Median values of saturated hydraulic conductivity (Ks) (metres per day) for two soil layers at Black Spur, estimated using three different measurement methods (after Davis et al. 1997). BP = borehole permeameter, SC = small cores and LC = large cores.

smaller, median values ranging between 1.6 m/d for the LC method and 0.09 m/d for the other two methods.

Variability among replicate measurements was highest using the SC method and lowest using the BP method. We attributed the high Ks values from the LC method to the fact that the cores were wide enough to contain macropores, but too short to contain the full (and finite) length of most macropores. Hence, there was a tendency for water to flow through the macropores and out the bottom of the core, whereas in the field, the finite length of the macropore would limit water flow.

How does Ks vary across a typical forest catchment?

Hydrologists working at the catchment scale need to balance the need for accurate point measurements of Ks against the need to make many measurements to contend with soil heterogeneity. For our study sites, we observed that the magnitude of Ks variation in space is much greater than the variation between Ks measurement methods at a point. Hence, we chose to measure Ks at many locations using the most practical method, the borehole permeameter (BP) technique.

In our study we were concerned not only with the absolute variability of Ks across catchments, but also with the spatial distribution of Ks values. This is important, because Topog is a so called 'distributed' model. When defining the input Ks values for Topog, decisions had to be made about what Ks values to ascribe to different parts of the catchment being modelled. For instance, should valley bottoms be ascribed higher values than ridge tops, or vice versa? Alternatively, does Ks simply vary randomly across the catchment?

We made a total of 105 Ks measurements along three transects in the Ettercon-3 catchment using the BP method. These were made at various depth intervals at 20 m spacings along three transects. Each transect ran from one ridge top, across the valley axis and up to the opposite ridge top, thus covering most topographic positions in the catchment.

Table 7 provides a statistical summary of the 34 Ks values obtained for the deepest soil layers measured (150–190 cm), considered to have the most effect on the catchment runoff behaviour. Ks varied between 0.02 and 1.73 m/d, with an overall median value of 0.37 m/d. The full distribution of values is shown in Figure 35a. There was no statistical difference between the values from the three transects, and no trend was evident in the distribution of Ks values with regard to position along the transects. We thus concluded that for modelling purposes, there was no basis for distributing Ks values in anything but a random pattern in space.

	T1	T2	T3
Minimum	0.14	0.02	0.06
Median	0.37	0.30	0.51
Maximum	1.73	0.65	1.11

Table 7: Statistical summary of the 34 Ks values (m/d) obtained at a depth of 150-190 cm for three measurement transects (T1-T3) in the Ettercon-3 catchment.

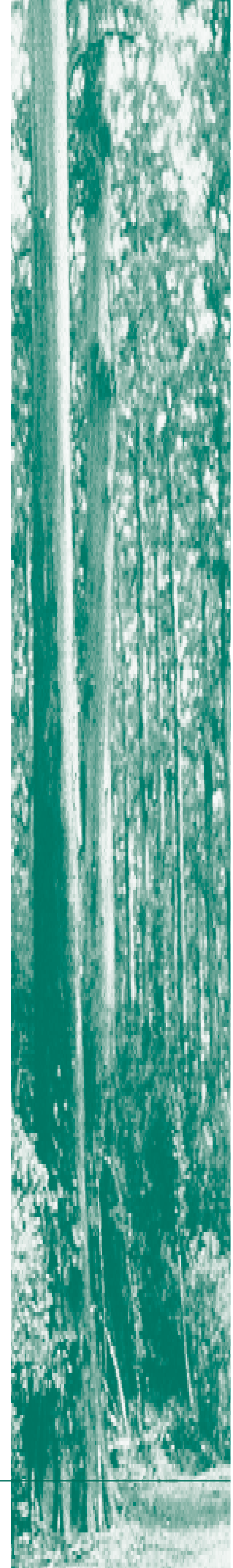
How important is Ks accuracy for a catchment simulation?

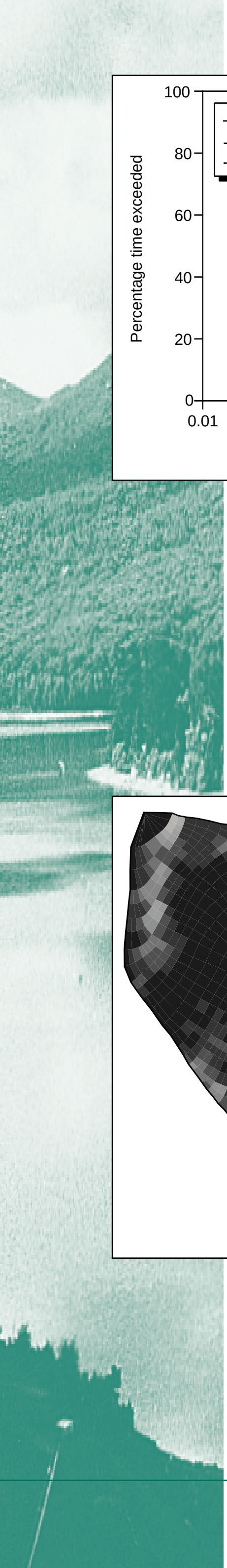
Of all the input parameters to the Topog model, Ks has the biggest effect on the timing and magnitude of runoff predictions. Unfortunately, as noted earlier, it is also the most difficult catchment property to measure accurately. We performed a variety of model sensitivity analyses to determine the implications of using poor Ks data in a catchment simulation. Specifically, we evaluated:

- the effects of using different 'best estimates' of catchment Ks, based on different measurement methods
- the need (or not) to represent spatial variability in Ks in catchment simulations.

As noted earlier, Ks values obtained for the Black Spur site with the small core and large core measurement methods were very different, having median values of 0.09 and 1.6 m/d, respectively, between 50 and 500 cm depth. These values were used in Topog simulations of water movement through the Myrtle-2 catchment to compare their effect on predicted runoff and watertable patterns.

Figure 33 shows that the large core data yielded a distribution of runoff values similar to observed values. However, the small core data resulted in poor predictions of daily runoff, with many unrealistically low and high





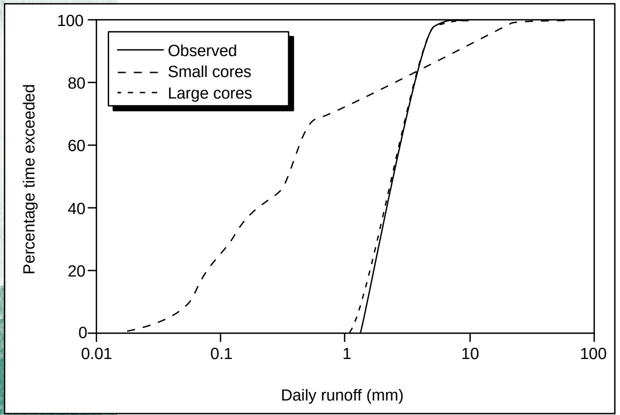


Figure 33: Observed and predicted daily flow durations for the Myrtle-2 catchment. Two predictions are shown—one based on small core Ks data and the other based on large cores.

runoff events predicted. Figure 34 shows that the simulations based on small core Ks data predict (quite unrealistically) that the watertable is close to the surface throughout the catchment. The simulations based on large core Ks data, however, yield spatial patterns of watertable depth which accord with our field observations. These results emphasise the importance of scale in field measurement methods—the large core method represented the important process of preferential flow, which was not taken into account in the small core method.

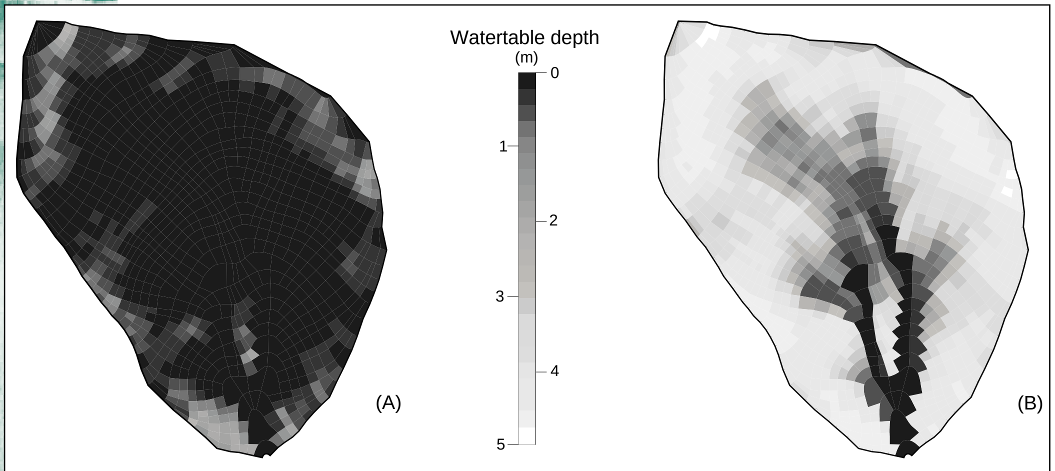


Figure 34: Topog predictions of water table depth across the Myrtle-2 catchment on a winter day, illustrating the implications of using Ks data obtained using small cores (A) and large cores (B). The pattern predicted in (B) accords with field observations.

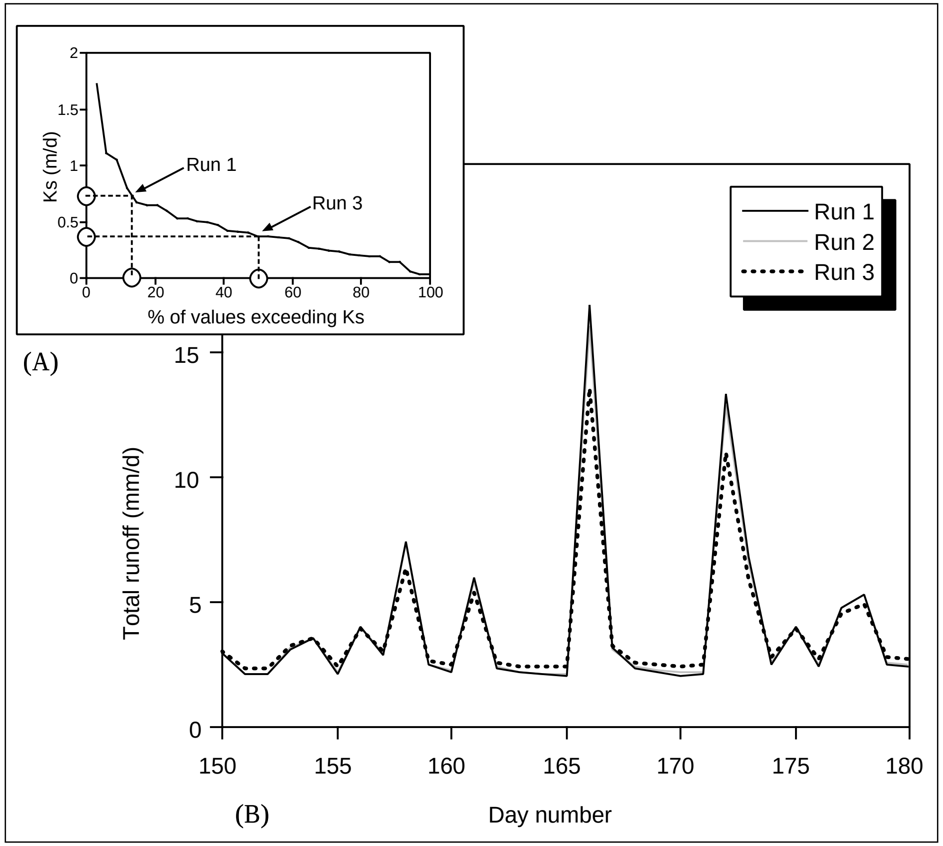


Figure 35: (A) Cumulative frequency distribution of saturated hydraulic conductivity (Ks) values for the 150–190 cm soil layer, measured in the Ettercon-3 catchment. (B) Comparison of three different daily runoff predictions for the Ettercon-3 catchment, using different Ks values for the 150-190 cm soil layer.

Earlier, we also noted that Ks varies considerably across the Ettercon-3 catchment in a seemingly random manner. Using Topog, we performed three different one-year simulations for this catchment to determine whether or not it was important to represent spatial variability in Ks. In all three runs, we used single median values of Ks for the upper soil layers, but we varied the Ks values for the deepest layer (150–190 cm) between runs. In run 1, we used the median value for the deepest soil layer. In run 2, we randomly distributed a range of Ks values taken from the full data distribution shown in Figure 35(A).

In run 3, we again used a single Ks value for the deepest soil layer, equivalent to double the actual median value.

The results for these three simulations are shown in Figure 35(B), focussing on predicted daily runoff over a 30-day period in winter. They show that there is very little difference between the predictions for runs 1 and 2, demonstrating that it is not important to spatially distribute Ks values in space. What is important is to adopt an accurate ‘representative’ value of Ks for the catchment; the median value is recommended as Ks data is usually log-normally distributed. By doubling Ks in run 3, baseflow was increased and runoff peaks were lowered, relative to run 1. Total annual runoff increased by about 10% for this simulation. This illustrates the impact of using the wrong ‘representative’ value of Ks. In conclusion, it seems necessary to make many measurements to properly characterise Ks for a catchment, though it is not necessary to explicity represent spatial variability in Ks by distributing values across the catchment.

Limitations of the Topog model

While the Topog model has performed well for the Myrtle-2 and Picaninny catchments, we recognise that it has several limitations.

Firstly, like most models of this kind, Topog is complex to apply. The need for judicious input value selection and careful interpretation of results demands that a well-trained hydrologist run the model. For instance, we showed above how important it is to gather accurate Ks data to run the model and the implications of using poor data. Topog is clearly not a management-oriented model, but can produce useful results for managers if applied properly.

The second limitation relates to the scale at which the model can be applied. Because of the need for detailed input data and the speed at which Topog performs computations, it is really only practical to apply to catchments up to 10 km^2 in area for long term water balance simulations.

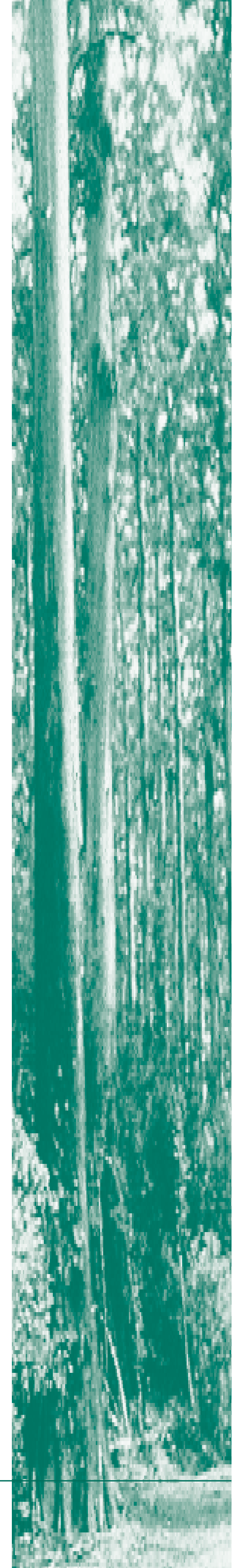
The third, and perhaps most serious, limitation relates to the forest growth predictions in the model. At this stage, Topog is unable to model the natural thinning behaviour of the mountain ash forest, a problem that did not appear in the Picaninny application because leaf area was always increasing. The model predicts leaf area recovery from disturbance well, but once the maximum leaf area index (LAI) is attained, it will not decrease in the model unless there are adverse environmental conditions such as water, nutrient or salinity stress. These stresses rarely exist in the mountain ash forest so, for the moment, the problem can only be overcome by imposing the temporal changes in LAI as an input, rather than simulating them.

Fortunately, we now have a good understanding of how mountain ash LAI changes with time (Figure 15), so the water balance effects of long term changes in LAI can still be predicted. In the next section, we will see how this information was successfully used in large scale modelling.

Large scale catchment modelling

While models such as Topog can provide helpful insights into small catchment behaviour, many management questions are posed at the large catchment scale. By ‘large’ we mean something like the watershed of a reservoir, typically 100–1000 km^2.

In response to this need, we built a model called Macaque. This has many features in common with Topog, particularly the way in which it estimates evapotranspiration. However, Macaque uses a vastly simplified soil moisture balance scheme and an efficient representation of flow pathways.



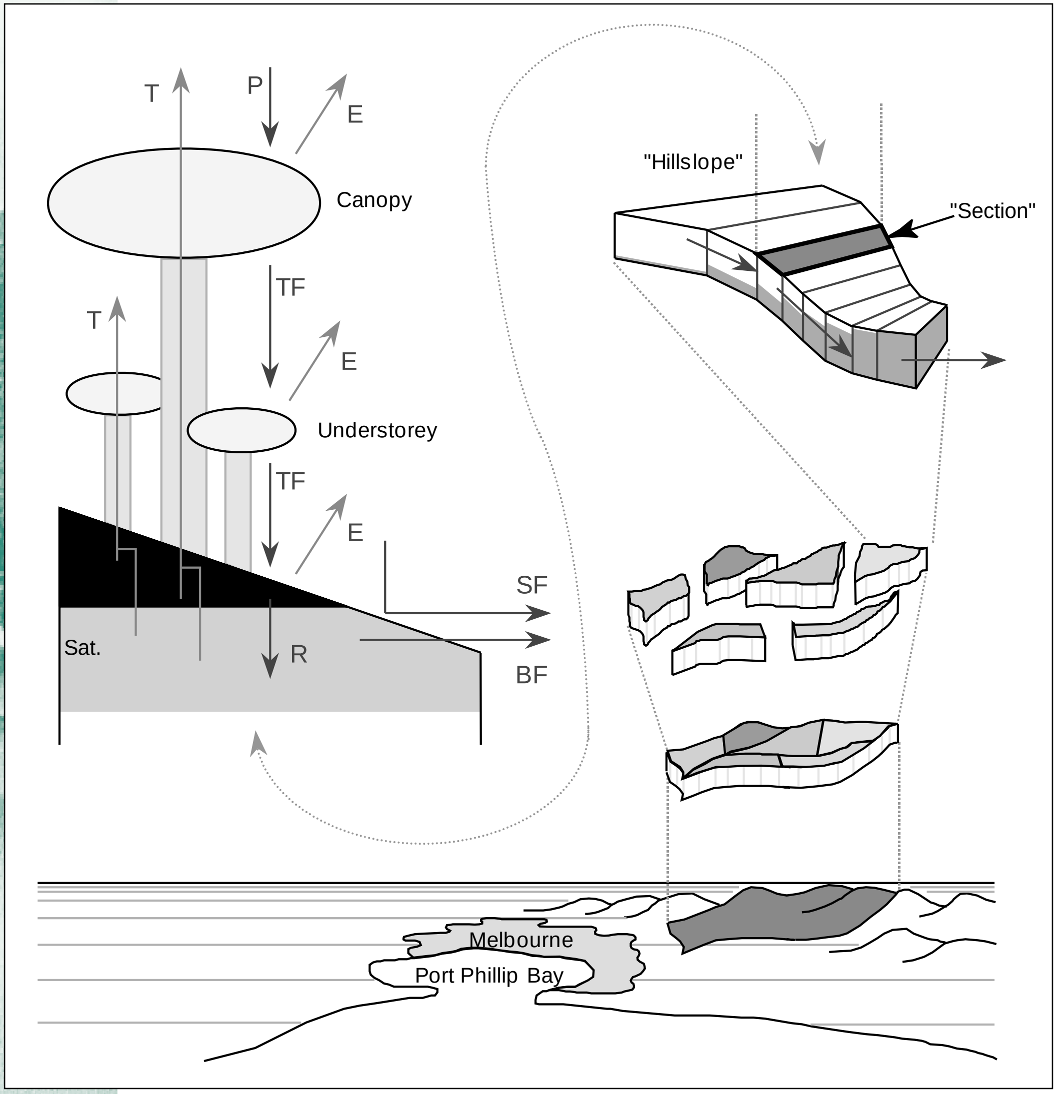


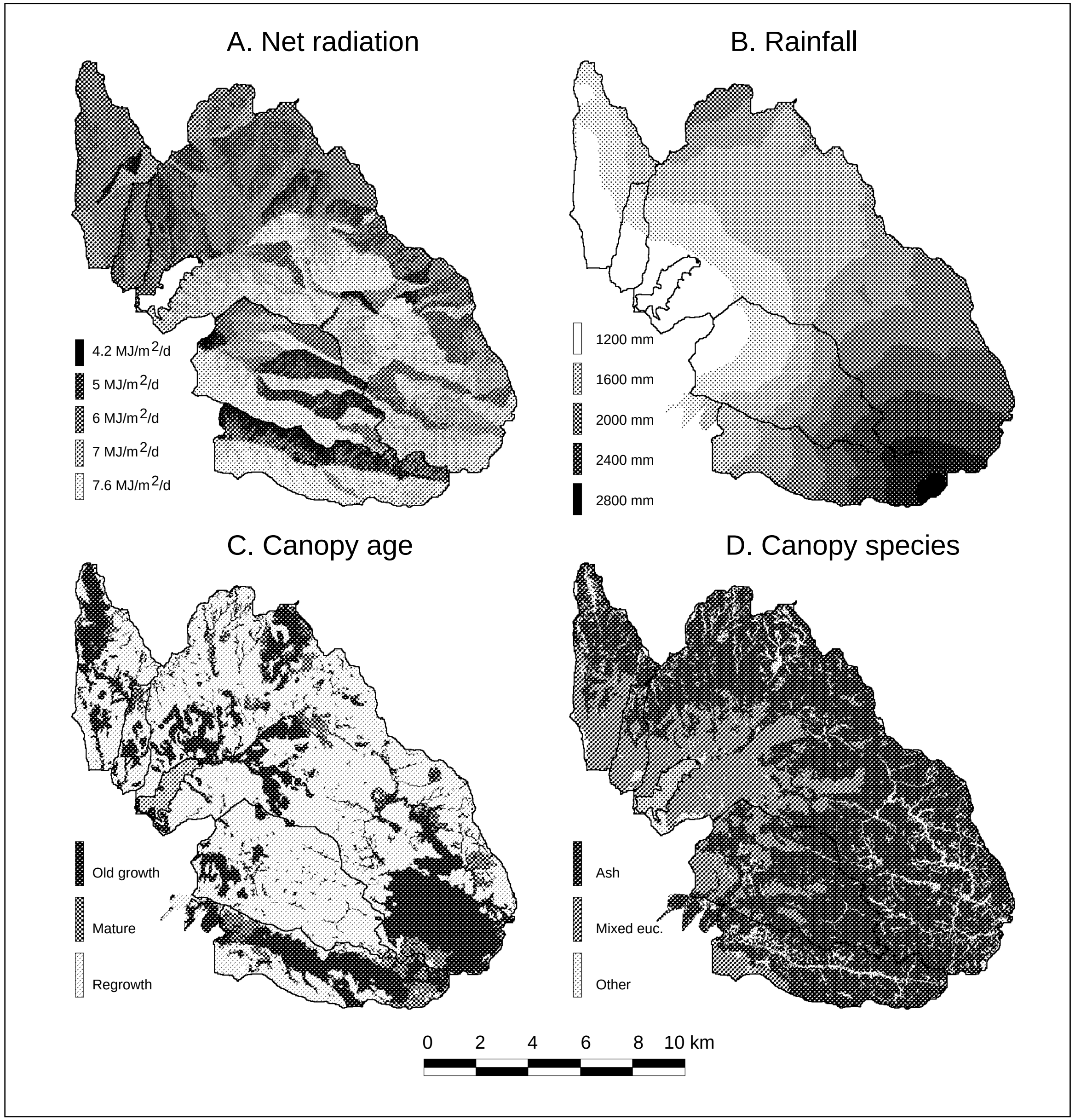
Figure 36: Schematic representation of the structure of Macaque. P = precipitation, TF = throughfall, T = plant transpiration, E = evaporation, R = recharge, SF = stormflow, BF = baseflow.

This permits application of the model to much larger spatial scales than is possible with Topog. Like Topog, Macaque is driven by daily values of temperature, humidity, radiation and rainfall. It predicts daily values of soil moisture content, evapotranspiration and runoff.

Figure 36 summarises the structure of Macaque. Large catchments are divided into a number of individually treated 'hillslopes'. Each hillslope is divided into 'sections' defined by a wetness index, which quantifies where each point in the hillslope lies on a scale from 'ridge-top' to 'valley-bottom'. Finally, within each section, a water balance similar to that solved by Topog is calculated. There are two vegetation layers and an evaporating soil/litter layer. In the sub-surface, there are just two soil layers—a saturated zone and an unsaturated zone.

Mapping large catchments using a geographic information system

Before we can model large natural systems we must first map them, usually by means of a geographic information system (GIS). In mapping our target site, the Maroondah water supply catchments (163 km^2), we had to contend with a great deal of variation in landscape parameters to which the catchment water balance is sensitive. There was wide topographic variation in variables such as elevation (which greatly influences temperature and precipitation) and aspect (which influences the amount of radiation energy received at the land surface). A complex mosaic of forest types existed, with vegetation age and overstorey species being two variables that significantly influenced transpiration rates. Finally, and probably most importantly, rainfall varied markedly across the basin, mainly with respect to elevation, but also as a function of site exposure to prevailing winds. Examples of the spatial maps that underpin a Macaque catchment analysis are illustrated in Figure 37. These include net radiation, rainfall, canopy species and canopy age.

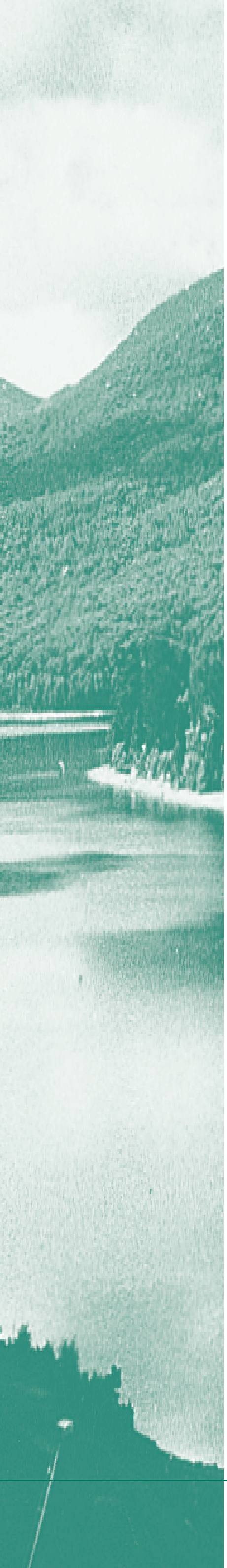


Testing Macaque at the Maroondah catchments

Macaque was applied to the Maroondah catchments and used to simulate the hydrologic effects of the 1939 fires, which burnt most of the area. Daily runoff was simulated over an 82 year period spanning the fires (1911–1992) and compared with observed streamflow summed from the three largest catchments (Watts, Graceburn and Coranderrk). As in the Topog applications reported earlier, most model parameter values were based on published or measured data. A ten year calibration period (1980–1989) was used. We compared model predictions and field observations of streamflow, throughfall, transpiration, soil evaporation, groundwater elevations and soil moisture levels. By testing the model against such a range of variables, we reduced the risk of obtaining 'the right model results for the wrong reason'.

Predicted and observed runoff compared well at daily, weekly, monthly and yearly time scales. Figure 38 shows predicted annual runoff for the simulation period, plotted against observations.

Figure 37: Examples of spatial maps underpinning a Macaque analysis. Net radiation is for a typical day in winter. Rainfall is the average annual total. Canopy age and species types have been lumped into three classes for clarity.



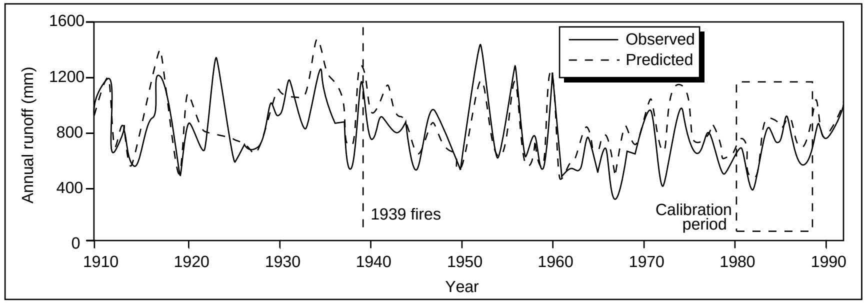


Figure 38: Predicted and observed annual runoff (mm) from the three largest Maroondah catchments.

The model was able to explain 66% of the variance in observed yearly runoff. The primary source of the unexplained variance in the predictions was not so much poor model structure or parameters, but error in the estimation of daily catchment precipitation. Macaque is driven by a rainfall surface which, for the current application, was calculated from a single rain-gauge, and assumed to be the same for all storms. In future applications of the model, we plan to relax this assumption by calculating the rainfall surface from multiple gauges.

Using Macaque to predict the hydrologic impact of fire

After we were satisfied that Macaque could produce realistic simulations of the catchment water balance, we decided to predict a typical catchment management scenario. Macaque was run for an 80 year period starting in 1920, with a vegetation mosaic thought to have existed at that time. All mountain ash vegetation was assumed to be old growth at the start of the simulation and killed by 1939 fires. To smooth out the catchment response, the daily climate values for 1958 were used throughout the simulation. In 1958, annual precipitation and maximum and minimum temperature differed from the long term average by less than 3%.

Figure 40: Predicted annual runoff before and after a wildfire for hillslopes A, B and C in Figure 39.

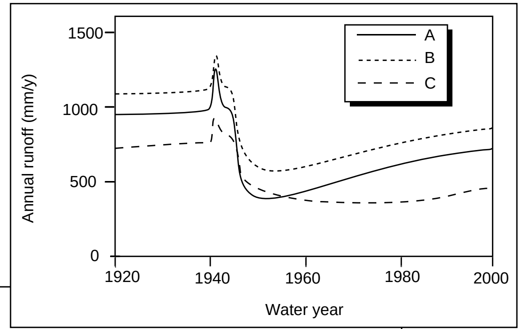


Figure 39: Map of predicted decline in water yield following wildfire in the Maroondah catchments. (See Figure 40 for further explanation.)

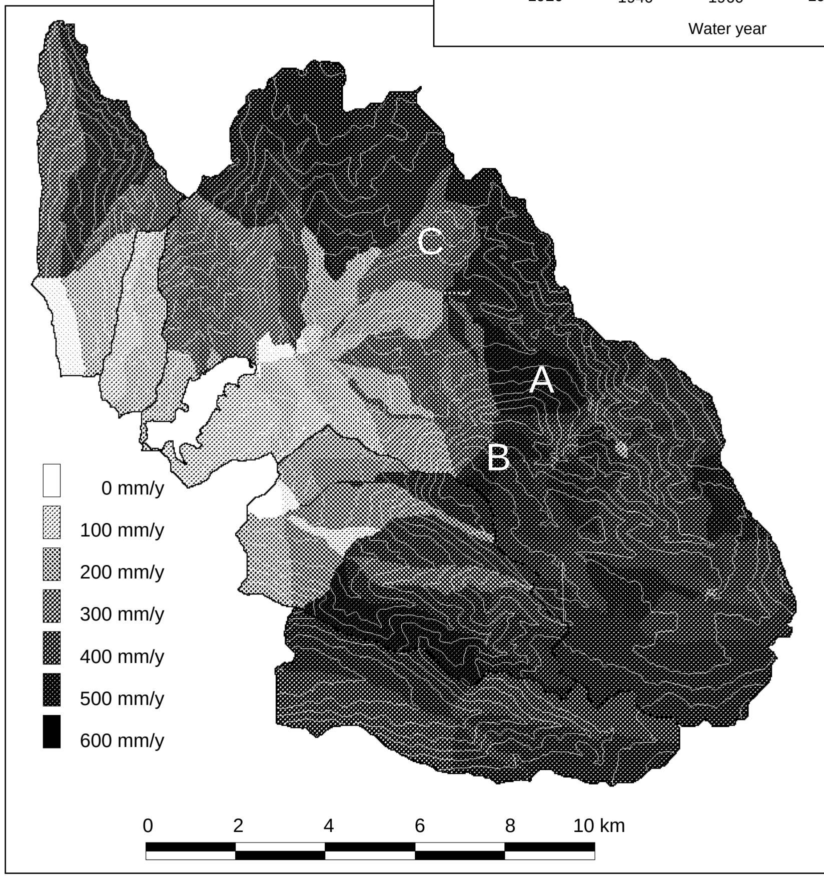


Figure 39 shows a map of the predicted decline in water yield, indicating which areas are least and most affected by the fire. The values plotted are the difference between runoff predicted for 1920 (pre-fire) and 1960 (20 years post-fire). As expected, the areas covered by mountain ash forest are worst affected. Within these areas, hillslopes receiving most radiation (Figure 37A) tend to exhibit the greatest runoff decline, though the variation is modest.

Figure 40 shows hydrographs predicted for three hillslopes, marked in Figure 39 as A, B, and C. All three hillslopes are primarily forested with mountain ash, along with small areas of streamside rainforest. Hillslopes A and B display similar runoff responses to disturbance, both resembling the Kuczera curve shown in Figure 10 (page 7). Hillslope C however exhibits a smaller decline in runoff than the other two hillslopes. Further, a significant delay exists in the time taken to reach minimum runoff, apparently related to extensive areas of the hillslope that are only connected to the stream through slow, subsurface pathways.

While these observations are preliminary, they illustrate the ability of Macaque to predict variations in hydrologic response to disturbance across a large catchment. The above scenario simulated the effects of fire over the entire region, but the impact of local changes (such as discrete logging coupes) can also be simulated.

Improving the Macaque simulations

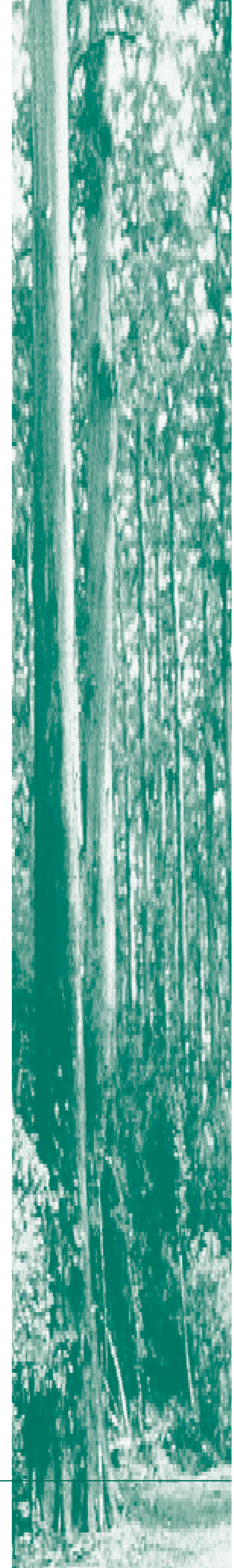
While initial modelling results from Macaque have been encouraging, there are several ways in which the simulations could be improved.

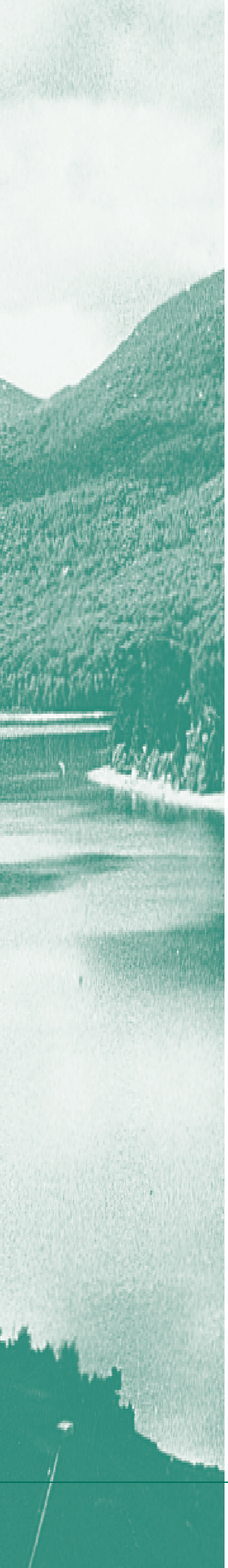
First, as noted earlier, our reliance on a single rain-gauge to generate the daily rainfall surface for the study area probably introduces error. This is not an inherent limitation of the model, as it can be overcome by utilising more data.

Second, we have assumed that mountain ash leaf area index (LAI) varies according to the pattern shown in Figure 15, wherever this species grows in the Maroondah catchments. In reality, Figure 15 is based on data gathered from a small part of the total study area, and we would expect the LAI response to vary with differences in radiation, temperature and rainfall. In future, Macaque could be adapted to simulate growth as in Topog. Alternatively, some simple equations could be developed to spatially modulate the LAI curve that we have used. For instance, we might permit LAI to rise to as high as 5.0 on the wetter and more shaded sites, but impose a limit of 3.0 at the drier and more exposed sites.

Third, in the simulations conducted so far, we have assumed soils to be uniform in depth and conductivity, although we know that this is definitely not so in the Maroondah catchments. For instance, we have observed that soils tend to be shallower and stonier on north facing slopes. These soils would have a lower water holding capacity and would thus affect the growth and transpiration behaviour of the forest. Variations in soil properties across the study area would have a minor effect on the total water budget, but would significantly affect the shape of the daily runoff hydrograph at particular locations.

Fourth, as with Topog, Macaque must be run on a high speed UNIX workstation. We are planning to develop a PC version of the software soon, along with a user interface that will make the model both portable and easier to use.





SUMMARY OF PROJECT OUTCOMES

This project has:

- explained how different components of the mountain ash forest water and carbon balance vary through time resulting in runoff changes,
- developed and verified a small scale catchment model (Topog) to predict the long-term water and carbon balance of mountain ash forest catchments up to 10 km^2 in area,
- developed and verified a large scale catchment model (Macaque) to predict the long-term water balance of mountain ash forest catchments up to 1000 km^2 in area, and
- improved the ability of catchment managers to forecast the likely water yield changes resulting from forest disturbance in different parts of the mountain ash forest resource.

FUTURE RESEARCH DIRECTIONS

The experimental methods and modelling tools developed in this project are now being used to:

- evaluate whether or not evapotranspiration (and hence runoff) changes as other types of eucalypt forest age. A major focus of this work is the 'drier' silvertop ash (*E. sieberi)* forests in south eastern New South Wales,
- determine how eucalypt plantations will grow and interact with the catchment water balance, depending on the position and density of plantings,
- predict the water yield consequences of broad scale afforestation in south eastern Australia.

These activities are being undertaken in the Cooperative Research Centre (CRC) for Catchment Hydrology Project FO2, entitled 'Impacts of forest management and plantation establishment on catchment water balance'. Further information on this project can be obtained from the CRC for Catchment Hydrology, or from the project leader, Dr Rob Vertessy.

Research contacts

Rob Vertessy (Project Leader, A2)
CSIRO Land and Water
Canberra
ph: (02) 6246 5790
fax: (02) 6246 5845
email: rob.vertessy@cbr.clw.csiro.au

Fred Watson
Dept Civil & Environmental Engineering
University of Melbourne
ph: (03) 9344 7237
fax: (03) 9344 6215
email: fgrw@civag.unimelb.edu.au

Sharon O'Sullivan &
Sharon Davis
c/o CRC Centre Office
Dept Civil Engineering
Monash University, Clayton
ph: (03) 9905 2704
fax: (03) 9905 5033

Richard Benyon
CSIRO Division of Forestry and Forest Products
Canberra
ph: (02) 6281 8272
fax: (02) 6281 8312
email: richard.benyon@cbr.for.csiro.au

Further reading

Ashton, D.H. (1975) The root and shoot development of *Eucalyptus regnans* F Muell. Australian Journal of Botany, 23: 867–887.

Ashton, D.H. (1976) The development of even-aged stands of *Eucalyptus regnans* F Muell. in central Victoria. Australian Journal of Botany, 24: 397–414.

Band, L.E., Vertessy, R.A. and Lammers, R. (1995) The effect of different terrain representations and resolution on simulated watershed processes. Zeitschrift für Geomorphologie, Suppl.-Bd. 101: 187–199.

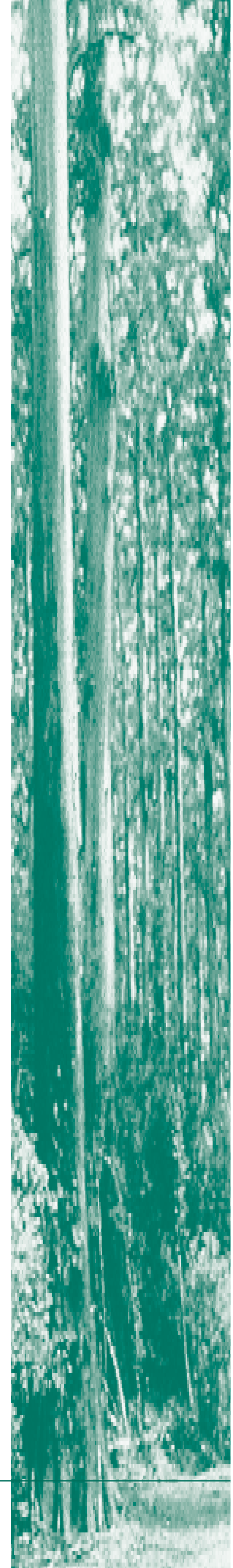
Bosch, J.M. and Hewlett, J.D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55: 3–23.

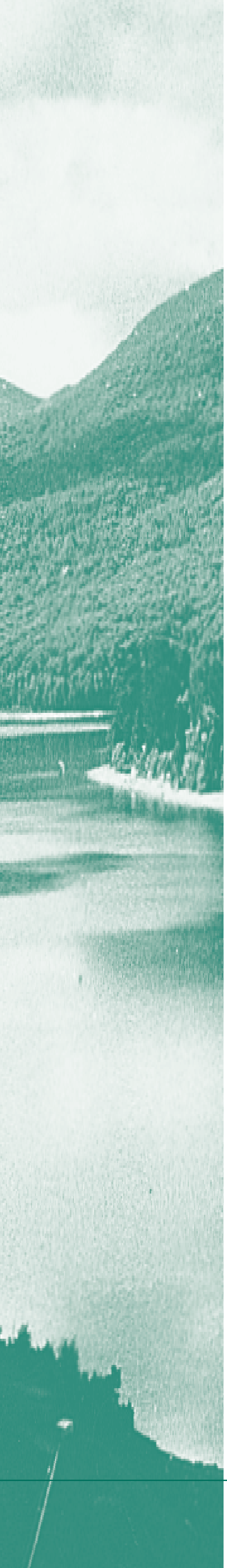
Cornish, P.M. (1989) The effects of radiata pine plantation establishment and management on water yields and water quality—a review. Technical Paper No. 49, Forestry Commission of New South Wales, 53 pp.

Davis, S., Vertessy, R.A., Dunkerley, D.L. and Mein, R.G. (1996) The influence of scale on the measurement of saturated hydraulic conductivity in a forest soil. In Proceedings of *The 23rd Hydrology and Water Resources Symposium*, Hobart, May 1996, pp. 103–108.

Davis, S.H., Vertessy, R.A. and Silberstein, R. (1997) The sensitivity of a catchment model to soil hydraulic properties obtained by using different measurement techniques. In Proceedings of *The International Congress on Modelling and Simulation (MODSIM 97)*, Hobart, 8–11 December, 1997, pp. 311–316.

Davis, S.H. (in prep.) The influence of scale on the measurement of saturated hydraulic conductivity in a forest soil. Ph.D thesis in preparation, Department of Civil Engineering, Monash University.





Dawes, W. and D.L. Short (1994) The significance of topology for modeling the surface hydrology of fluvial landscapes. Water Resources Research, 30(4): 1045–1055.

Dunn, G.M. and D.J. Connor (1993) An analysis of sap flow in mountain ash (*Eucalyptus regnans*) forests of different age. Tree Physiology, 13: 321–336.

Dye, P.J. (1996) Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Review, 75(1): 31–38.

Hatton, T.J., Dawes, W.R. and Vertessy, R.A. (1995) The importance of landscape position in scaling SVAT models to catchment scale hydroecological prediction. In: R.A. Feddes (ed.) *Space and Time Scale Variability and Interdependencies in Hydrological Processes*, pp. 43–53 (Cambridge University Press: Cambridge).

Haydon S.R., Benyon, R.G. and Lewis, R. (1996) Variation in sapwood area and throughfall with forest age in mountain ash (*Eucalyptus regnans*, F. Muell). Journal of Hydrology, 187: 351–366.

Holmes, J.W. and Sinclair, J.A. (1986) Water yield from some afforested catchments. In Proceedings of the *Hydrology and Water Resources Symposium*, The Institution of Engineers, Australia, Brisbane, 25–27 November 1986, pp. 214–218.

Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S. and Lynch, J.A. (1993) Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology, 150: 323–344.

Jayasuriya, M.D.A., Dunn, G., Benyon, R., and O'Shaughnessy, P.J. (1993) Some factors affecting water yield from mountain ash (*Eucalyptus regnans*) dominated forests in south-east Australia. Journal of Hydrology, 150: 345–367.

Kuczera, G.A. (1985) Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Melbourne and Metropolitan Board of Works, Catchment Hydrology Research Report, MMBW-W-0014.

Kuczera, G.A. (1987) Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Journal of Hydrology, 94: 215–236.

Langford, K.J. (1976) Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. Journal of Hydrology, 29: 87–114.

Langford, K.J. and O'Shaughnessy, P.J. (eds.) (1977) First Progress Report, North Maroondah. Melbourne and Metropolitan Board of Works, Catchment Hydrology Research Report, MMBW-W-0005.

Langford, K.J. and O'Shaughnessy, P.J. (1980) Second Progress Report—Coranderrk. Melbourne and Metropolitan Board of Works, Catchment Hydrology Research Report, MMBW-W-0010.

McCulloch, S.G. and Robinson, M. (1993) History of forest hydrology. Journal of Hydrology, 150: 189–216.

McJannet, D.L., Vertessy, R.A., Tapper, N.J., O'Sullivan, S.K., Beringer, J. and Cleugh, H. (1996) Soil and litter evaporation beneath regrowth and old growth mountain ash forest. Cooperative Research Centre for Catchment Hydrology Report No. 96/1, Monash University, Victoria, Australia, 60 pp.

O'Sullivan, S.K. (in prep.) The relationship between leaf area, transpiration and canopy interception in various age classes of *Eucalyptus regnans*. Ph.D thesis in preparation, Department of Civil Engineering, Monash University.

Read, Sturgess and Associates (1992) Evaluation of the economic values of wood and water for the Thomson catchment. Report prepared by Read, Sturgess and Associates, Consulting Economists, 165 pp.

Ruprecht, J.K. and Stoneman, G.L. (1993) Water yield issues in the jarrah forest of south-western Australia. Journal of Hydrology, 150: 369–391.

Schofield, N.J. (1996) Forest management impacts on water values. Recent Research Developments in Hydrology, 1: 1–20.

Vertessy, R.A., Hatton, T.J., O'Shaughnessy, P.J. and Jayasuriya, M.D.A. (1993) Predicting water yield from a mountain ash forest catchment using a terrain analysis-based catchment model. Journal of Hydrology, 150: 665–700.

Vertessy, R., Benyon, R. and Haydon, S. (1994) Melbourne's forest catchments: effect of age on water yield. Water, 21(2): 17–20.

Vertessy, R., Benyon, R., O'Sullivan, S. and Gribben, P. (1994) Leaf area and tree water use in a 15 year old mountain ash forest, central highlands, Victoria. Cooperative Research Centre for Catchment Hydrology Report No. 94/3, Monash University, Victoria, Australia.

Vertessy, R.A., Benyon, R.J., O'Sullivan, S.K. and Gribben, P.R. (1995) Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. Tree Physiology, 15: 559–568.

Vertessy, R.A., Dawes, W.R., Zhang, L., Hatton, T.J. and Walker, J. (1996) Catchment scale hydrologic modelling to assess the water and salt balance behaviour of eucalypt plantations. In K.G. Eldridge, M.P. Crowe and K.M. Old (eds.) *Environmental Management: The Role of Eucalypts and Other Fast Growing Species*, pp. 110-121.

Vertessy, R.A., Hatton, T.J., Benyon, R.J. and Dawes, W.R. (1996) Long term growth and water balance predictions for a mountain ash (*E. regnans*) forest subject to clearfelling and regeneration. Tree Physiology, 16: 221–232.

Vertessy, R.A., Hatton, T.J., Reece, P., O'Sullivan, S.K. and Benyon, R.G. (1997) Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. Tree Physiology, 17(12): 747–756.

Vertessy, R., O'Loughlin, E., Beverly, E. and Butt, T. (1994) Australian experiences with the CSIRO Topog model in land and water resources management. In: Proceedings of *UNESCO International Symposium on Water Resources Planning in a Changing World*, Karlsruhe, Germany, June 28–30, 1994, pp. III–135–144.

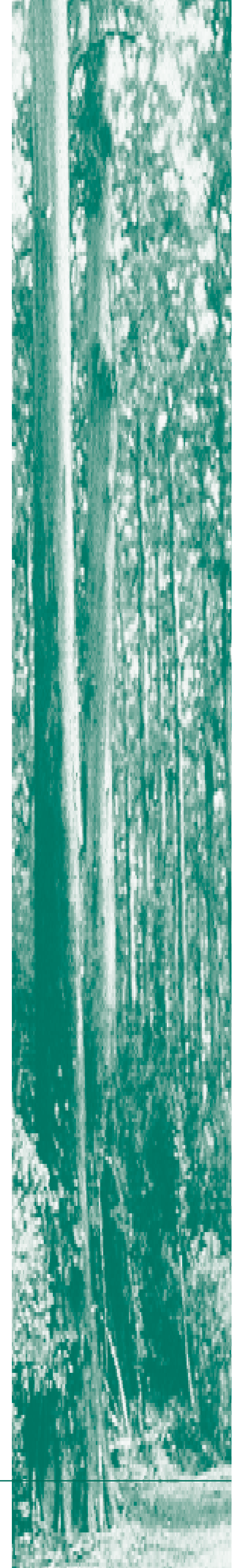
Watson, F.G.R., Vertessy, R.A. and Band, L.A. (1996) Distributed parameterisation of a large-scale water balance model for an Australian forested region. In proceedings of *HydroGIS '96, International Conference on Application of Geographic Information Systems in Hydrology*, Vienna, 16–19 April, 1996, pp. 157–166.

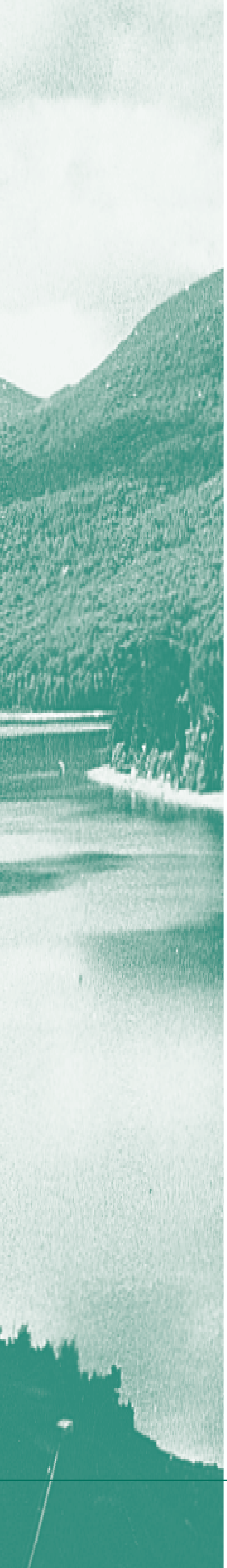
Watson, F.G.R. and Vertessy, R.A. (1996) Estimating leaf area index from stem diameter measurements in mountain ash forest. Cooperative Research Centre for Catchment Hydrology Report No. 96/7, Monash University, Victoria, Australia, 102 pp.

Watson, F.G.R., Vertessy, R.A., Grayson, R.B., Band, L.E. and McMahon, T.A. (1997) Macaque: regional scale modelling of water yield from forested basins. Water, 24(1): 10.

Watson, F.G.R., Vertessy, R.A. and Grayson, R.B. (1997) Large scale, long term, physically based prediction of water yield in forested catchments. In Proceedings of *The International Congress on Modelling and Simulation (MODSIM 97)*, Hobart, Tasmania, 8–11 December, 1997, pp. 397–402.

Watson, F.G.R., Grayson, R.B., Vertessy, R.A. and McMahon, T.A. (1998) Large scale distribution modelling and the utility of detailed ground data. Hydrological Processes, in press.





Watson, F.G.R. (1998) Large scale, long term, physically based modelling of the effects of land cover change on forest water yield. Ph.D thesis, submitted, Department of Civil and Environmental Engineering, University of Melbourne.

Zhu, A.X., Band, L.E., Vertessy, R. and Dutton, B. (1997) Derivation of soil properties using a soil land inference model (SoLIM). Soil Science Society of America Journal, 61(2): 523–533.

Established and supported under the Australian Government's Cooperative Research Centres Program

COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

A cooperative venture between:

Bureau of Meteorology
CSIRO Land and Water
Department of Natural Resources and Environment, Vic
Goulburn-Murray Water
Melbourne Water
Monash University
Murray-Darling Basin Commission
Southern Rural Water
The University of Melbourne
Wimmera-Mallee Water

Associates:

Department of Land and Water Conservation, NSW
Department of Natural Resources, Qld
Hydro-Electric Corporation, Tas
State Forests of NSW

Centre Office

Department of Civil Engineering
Monash University
Clayton, Victoria 3168 Australia
http://www-civil.eng.monash.edu.au/centres/crcch/