Hydrological studies into the impact of timber harvesting on water yield in state forests supplying water to Melbourne – Part 1 of Hydrological studies

eWater CRC

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Research Report for the Victorian Government

Hydrological studies into the impact of timber harvesting on water yield in state forests supplying water to Melbourne – Part 1 of Hydrological studies

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Summary

Melbourne's water supply is derived from its original "closed" catchments and from areas of State forest. The areas of State forest are managed for timber production under strict guidelines based on the Code of Forest Practices for Timber Production. The nature of timber harvesting activities undertaken in the State forests influences available water yield, and there has been a long history of debate about the relative costs and benefits of timber and water production from these areas.

The State Government's White Paper, *Securing Our Water Future Together* ("the White Paper") has sought to facilitate hydrological studies on the impact of timber harvesting on water yield for catchments in State forests supplying water to Melbourne. This report describes hydrologic modelling, undertaken in eight catchments, predominantly covered by State forests (Thomson, Armstrong Creek (Main and East), Cement Creek, McMahons Creek, Starvation Creek, Tarago and Bunyip), to assess the likely impact of timber harvesting on water yield.

Macaque a physically based hydrologic model developed by Watson (1999) and enhanced later by Peel *et al.* (2000) was applied to each catchment and calibrated against observed streamflow records. The calibrated models were then used to develop water yield curves based on vegetation type, stand age and mean annual precipitation. These curves can then be applied in the Department of Sustainability and Environment (DSE)'s Integrated Forest Planning System, to better determine the relative benefits of different forest management strategies

A sensitivity analysis was undertaken to examine the changes in flow and evapotranspiration (ET) in response to changes in leaf area index and in leaf conductance. Both flow and ET were found to be sensitive to changes in LAI or conductance.

The value of Macaque for planning and management of forested catchments has been confirmed in this study. The Department of Sustainability and Environment, and Melbourne Water can now test specific timber harvesting planning scenarios for the eight study catchments.

Acknowledgments

The following are thanked for their input into this study:

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Contents

1. Introduction

1.1 Relationship between forest age and water yield

Forest disturbance refers to changes in the structure of natural forests either by anthropological (e.g. timber harvesting) or by natural (e.g. bushfire) processes. This may lead to changes in forest type structure and/or density of vegetation, with consequent changes in evapotranspiration (ET) which is the product of transpiration, and interception and soil evaporation losses.

As a forest ages after disturbance, it changes from a very dense young forest to a mature (around 120 years) forest that exhibits large gaps in the overstorey canopy. It is the change in the density of forest stands with age that produces a marked difference in evapotranspiration (ET) and thus streamflow.

Many experimental studies investigating the hydrologic response of forest disturbance on ET and on catchment water yield have been carried out in eucalypt forests in Australia, particularly in the past two decades. This work has initiated from research carried out in the 1970s and 80s on the mountain ash forests that are dominated by *Eucalyptus regnans* and comprise much of Melbourne's water catchments. Langford (1976) demonstrated that regenerating *E.regnans* forests burnt in the severe 1939 bushfires were using more water than the mature forests they replaced. This work found there was an average 24% reduction in yield over 21 years following the fires, with yields diminishing beneath pre-fire levels within five years of the fires. These findings have been have been supported by a large body of research (eg. Kuczera, 1985, 1987, Vertessy *et al.*, 1993, 1996, 2001, Watson *et al*., 1999b, 2001), that have both confirmed the impacts and identified the causal processes.

The age/streamflow relationship for *E.regnan*s was generalised by Kuczera (1985, 1987) using rainfall and runoff data collected from eight forested catchments that were completely or partially burnt by a wildfire in 1939, and is represented by the well-known 'Kuczera curve' shown in Figure 1.1. The Kuczera curve predicts a decline in water yield of immediately after clearing, leading to a yield reduction of up to 50% at between 20 to 30 years, followed by a gradual rise back toward and old-growth or equilibrium water yield over the following 100-150 years. This curve has wide error bands (shown in Figure 1.1) indicating considerable uncertainty as to the absolute impact on yield. Nonetheless, this relationship has provided a useful tool when evaluating certain forest management options on catchment water yield (e.g. Mein *et al*., 1993).

The Kuczera curve does not include an initial yield increase immediately following stand mortality from fire. In practice, there is an initial increase in water yield (typically 5-10) years while ET is reduced, followed by a decline in yield as ET is increased as the stand regenerates. Generally, transpiration (overstorey and understorey) explains about three-quarters of the yield response and the remainder is explained by changes in canopy interception.

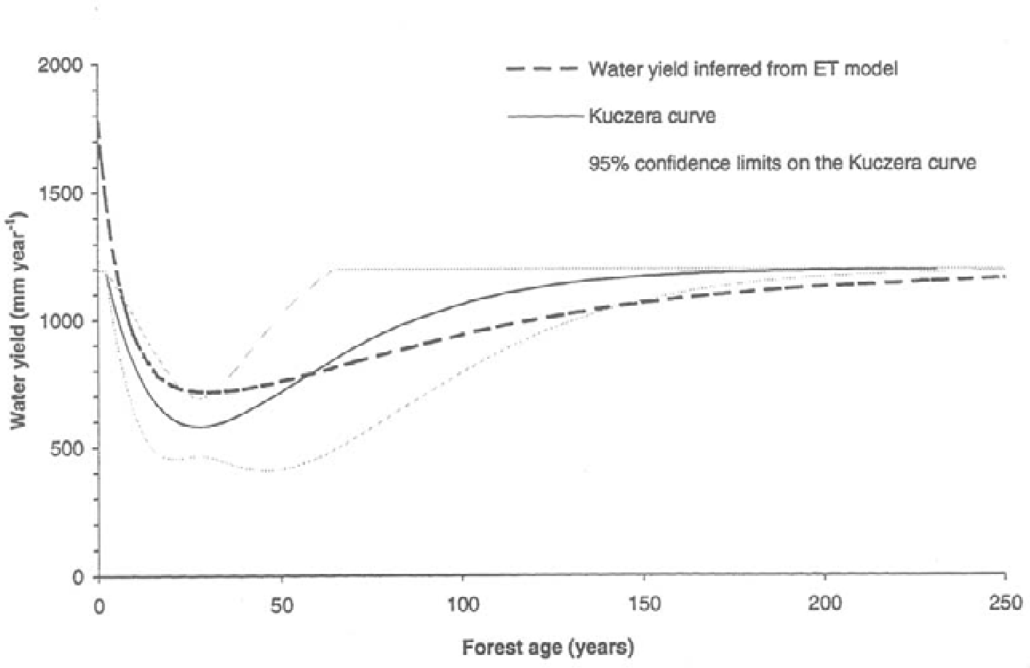

Figure 1.1. Generalised average annual water yield with forest age shown by the Kuczera curve (after Kuczera, 1987), and inferred from evapotranspiration, by Watson *et al.* (1999b). Dashed lines are 95% confidence intervals.

Watson *et a*l. (1999b) derived a revised relationship based on rainfall, transpiration and water yield data from smaller paired experimental catchments (Figure 1.1). This new curve is similar to the Kuczera curve, but includes a sharp initial increase in water yield above long term values in the first 5 years after disturbance, and then declines. This was considered to be an improvement to the Kuczera curve, because it considered a more detailed temporal scale in the analysis. The amplitude of the dip in the curve developed by Watson *et al* 1999b is less, because catchments that were not completely cleared were used in the analysis. Of relevance though, is the time to recovery, which is of importance to the long term planning of timber harvesting cycles. However, Watson *et al.* (1999b) noted that the new water yield curve should not be viewed as a replacement or improvement on the Kuczera curve, but that it showed that data from the experimental catchments could be synthesised in a single equation which matches the general form of our existing understanding of regional long term water yield patterns.

There has not been the same level of research into eucalypt mixed-species age/streamflow relationships, but studies have detected a similar, though subdued, response to clearfell logging (Cornish, 1993; Cornish and Vertessy, 2001; Lane and Mackay, 2001; Roberts et al. 2001). Although there have been no studies to date reporting on the hydrologic response of *E. delegatensis* to disturbance, it is assumed it will be of a similar nature to that of *E. regnans* because the ecological response to fire is comparable. Again, it may be assumed that the hydrologic response will be somewhat subdued compared with *E. regnans*.

1.2 Policy context and scope

Melbourne's water supply is derived from its original "closed" catchments and from areas of State forest. The areas of State forest are managed for timber production under strict guidelines based on the Code of Forest Practices for Timber Production, and in accordance with the policy framework "Our Forests Our Future", which provides for the sustainable management of Victoria's forests.

The nature of timber harvesting activities undertaken in the State forests influences the sustainability of available water yield, and there has been a long history of debate about the relative costs and benefits of timber and water production from these areas. The Melbourne Water Resources Strategy *21st Century Melbourne; a WaterSmart City, 2002,* again raised the issue of the impacts of forest harvesting activities within Melbourne's water supply catchments on water supply.

In response, the Government's White Paper, *Securing Our Water Future Together* ("the White Paper") affirmed that:

- Melbourne's original water supply catchments are closed catchments and are managed as national parks. Timber harvesting will continue to be banned in these catchment areas;
- Improved water yields within catchments that supply water to Melbourne are important in securing Melbourne's water supplies.

In addition, with a view to examining the feasibility of improving water yields from the water supply catchments located in State forests, it is stated (in Action 2.21) that the Government will, among other initiatives, undertake hydrological studies on the impact of logging on water yield of catchments in State forests supplying water to Melbourne. This report describes a research modelling study, undertaken in several catchments, to develop water yield curves based on vegetation type, stand age and mean annual precipitation. These curves can then be applied in the DSE's Integrated Forest Planning System, to better determine the relative benefits of different forest management strategies.

1.3 Project outline

In order to investigate the impact of timber harvesting on water yield of catchments in State forests supplying water to Melbourne, a hydrologic modelling exercise was undertaken with the following tasks.

1. Using the Macaque water yield model developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH), establish and calibrate Macaque water yield models which take into account forest vegetation conditions, physiographic factors, precipitation and hydrologic data for the:
    - Thomson catchment (building on previous Macaque models developed for the Thomson)
    - Yarra tributaries catchments (Armstrong Creek, Cement Creek, McMahons Creek and Starvation Creek catchments)
    - Tarago catchment; and
    - Bunyip catchment.

2. Conduct sensitivity analysis of the new Macaque water yield model, concentrating on the sensitivity of water yield to the adopted relationships between leaf area index (LAI) and age, and between leaf conductance and age.

3. Using the calibrated model parameters, develop water yield curves for each vegetation type in each of the above catchments.

The resultant Macaque-derived water yield curves for each catchment will then be integrated with the Integrated Forest Planning System (IFPS) by DSE in order to explore the impacts of various timber harvesting options on both timber and water yields. This will require the conversion of the water yield curves into yield tables and development of an IFPS model for each catchment. At present, it is not possible to represent thinning regimes (other than clearfelling) in Macaque. Even then, spatial lumping within Macaque makes it difficult to accurately define the spatial extent of harvesting coupes. Incorporation of yield curves derived from Macaque into the IFPS was the logical process to take in order to examine the impacts of thinning on water yield.

Further work within this project (not completed yet) will:

- undertake further modelling with Macaque to assess the impacts of various bushfire scenarios (to be determined by the Project Working Group)
- conduct modelling studies using CSIRO and Bureau of Meteorology data to estimate the impacts of various climate change scenarios (to be determined by the Project Working Group); and
- Prepare a final report on the timber and water yield outcomes of various management options in Melbourne's water supply catchments.

1.4 Report outline

Chapter 2 describes the catchments included in the study, while the chapter 3 provides an overview of the Macaque model, including data requirements. Model construction and calibration, including processes and results for each catchment, are presented in Chapter 4. Chapter 5 describes a sensitivity analysis of leaf area index and leaf conductance on water yield, and limitations and assumptions of the modelling process is presented in chapter 6. Chapter 7 describes the development of water yield curves (from Macaque model outputs) for inclusion into DSE's Integrated Forestry Planning System (IFPS). Conclusions drawn from this research project are discussed in Chapter 8.

2. The catchments

2.1 Introduction

The catchments included in this study are the Thomson, Cement Creek, Armstrong Creek, Starvation Creek, McMahons Creek, Tarago and Bunyip catchments. These catchments lie between 69 and 115 km to the east of the city of Melbourne, Victoria. There was some uncertainty in the precise geographic locations of the monitoring stations at the catchment outlets. Field visits were made to each of the catchments, and the exact location of weirs and monitoring stations was established using a GPS. The catchments, including respective areas, and coordinates of catchment oulets used for calibration purposes, are presented in Table 2.1. The catchment areas are those defined by a digital terrain analysis of a 40 x 40 m digital elevation model (DEM) in Macaque.

The observed stream record for the Cement Creek catchment was of insufficient length (2.5 years) to allow a meaningful calibration to be undertaken. The catchment is described here, but no yield curves could be developed for this catchment. The Amstrong Creek catchment is made up of two catchments; Armstrong Creek Main and Armstrong Creek East.

Table 2.1. List of catchments with water quantity monitoring stations used for calibration, their coordinates and corresponding upstream catchment areas.

Catchment	Station #	Station name	Easting (m)	Northing (m)	Area (km^2)
Thomson	-	Dam wall	447289	5811644	476.52
Armstrong Creek Main	229104	Armstrong Ck@ u/s of weir	399460	5834009	39.28
Armstrong Creek East	229107	Armstrong Ck East branch @ u/s of weir	399774	5833737	14.49
Cement Creek	-	Cement Creek East Branch	389473	5825628	14.25
McMahons Creek	229106	McMahons Ck @ u/s of weir	401631	5824703	39.52
Starvation Creek	229109	Starvation Ck @ u/s of weir	398468	5820584	31.31
Tarago (at Neerim)	228206	Tarago River @ Neerim	406363	5797767	78.86
Tarago (at Dam wall)	-	Dam wall	406552	5791373	112.87
Bunyip	228207	Bunyip River @ Headworks	389866	5800430	39.44

A map showing the location of the catchments in relation to the city of Melbourne is provided in Figure 2.1. A description of each catchment is provided in the following sections.

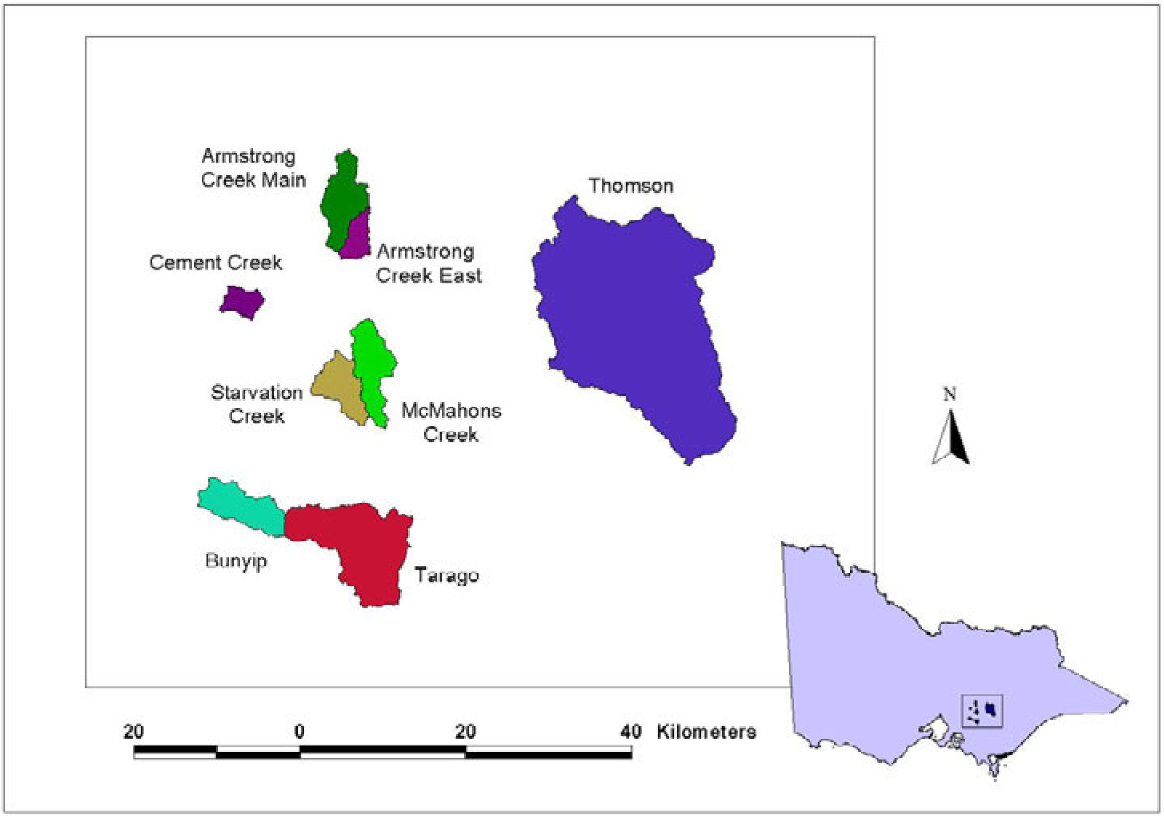

Figure 2.1. Map showing the location of the eight catchments included in this study.

2.2 Thomson

The Thomson catchment is located approximately 115km east of Melbourne. The Thomson catchment referred to in this report is defined as the catchment above the Thomson Reservoir outlet (447289E, 5811644N), with an area of 476.5km^2. Figure 2.2 shows a view of the reservoir from the dam wall.

Figure 2.2. View of the Thomson Reservoir from the dam wall. (*Source:* Melbourne Water).

The dam wall was constructed between 1976 and 1983. Water is supplied to Melbourne from the northern end of the Thomson Reservoir through a 19 km tunnel from Bells Portal, beneath the Great Dividing Range, and into to the Upper Yarra Reservoir, then onto Silvan Reservoir for distribution. Thomson Reservoir provides around 60% of the total storage capacity for the Melbourne system, and over the last 10 years approximately 31% of Melbourne's water supply has been sourced from this reservoir. In recent years, approximately 46% of reservoir inflow has been used to supply Melbourne and around 54% has been released for maintaining environmental flows and supplying irrigation areas downstream.

A digital elevation model of the catchment is shown in Figure 2.3. The terrain is steep and mountainous, ranging from 410 to 1560m above sea level.

A vegetation map of the Thomson catchment, and a table of vegetation abundances are presented in Figure 2.4 and Table 2.2 respectively. The catchment is completely forested, predominantly by mixed species forests, *Eucalyptus delegatensis* (Alpine Ash) and *E. regnans* (Mountain Ash). *Eucalyptus nitens*, (Shining Gum), *E. pauciflora* (Snow Gum) and *E. sieberi* (Silvertop Ash) also occur within the catchment.

The catchment geology comprises of Devonian granites (Baw Baw Plateau), Ordovician, Silurian and Devonian sediments (most of the catchment) and small patches of Tertiary volcanics and Quaternary alluvial deposits near Aberfeldy (DSE, 2004).

Soils within the catchment are a mixture of organic loams (Baw Baw plateau), with shallow stony loams leading down to red and brown earths towards the dam. The majority of the catchment is covered by brown earths, with shallow stony loams adjacent to the dam.

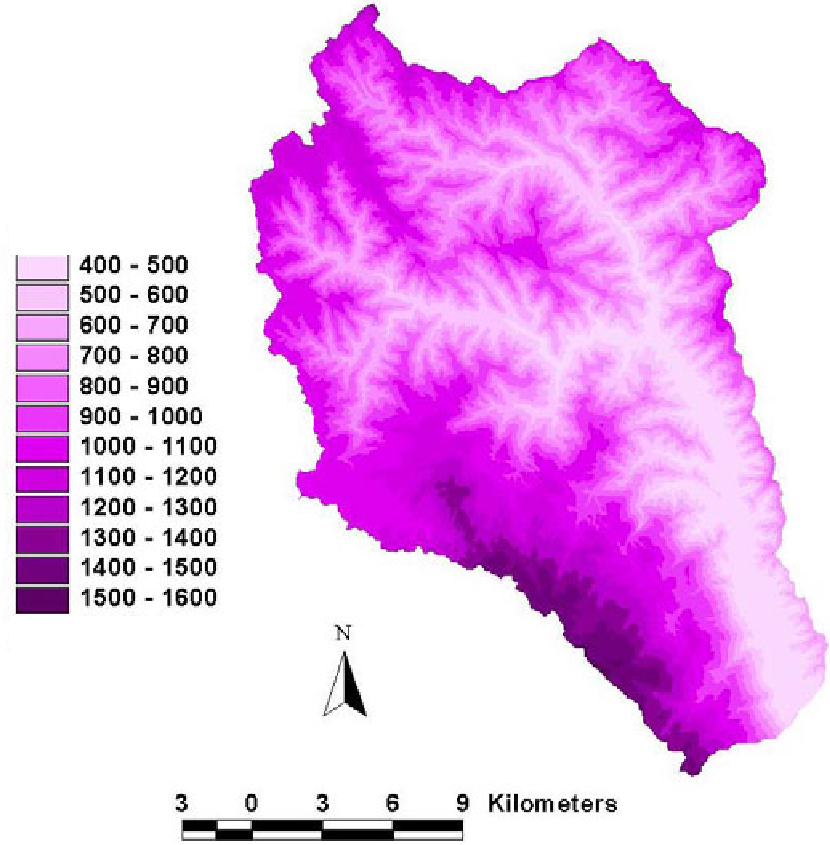

Figure 2.3. Digital elevation model (DEM) in metres (m) of the Thomson catchment.

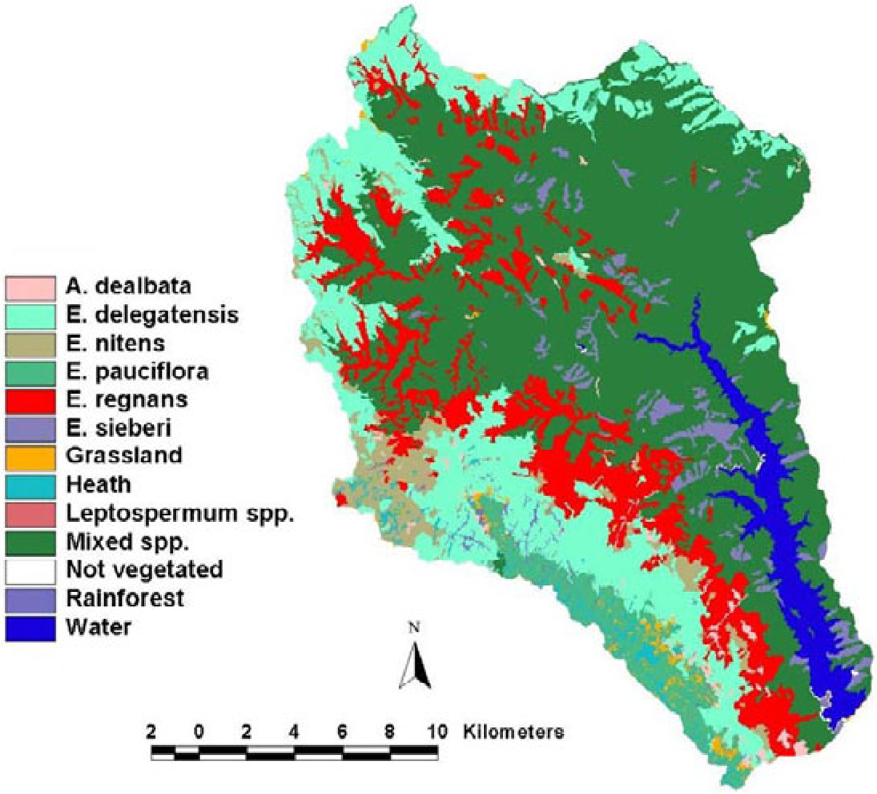

Figure 2.4. Vegetation type map for the Thomson catchment.

Table 2.2. Vegetation type by percentage in the Thomson catchment.

Vegetation type	Percentage
Mixed spp.	47.4
E. delegatensis	19.9
E. regnans	14.0
Water	4.5
E. nitens	3.9
E. pauciflora	3.9
E. sieberi	3.1
Heath	1.0
A. dealbata	1.0
Grassland	0.66
Rainforest	0.36
Not vegetated	0.13
Leptospermum spp.	0.12

2.3 Yarra tributaries

The Yarra tributaries, comprising Armstrong Creek (Main and East), Cement Creek, McMahons Creek and Starvation Creek catchments, cover an area of approximately 15,000 ha (150 km2) and collectively provide Melbourne with approximately 6% of its water supply. In response to earlier years of drought, water was diverted from these catchments to supply water to Melbourne starting between 1968 and 1971.

Approximately 60-70ha, or 0.4% of the total area is planned to be harvested for timber in an average year. In any year, one of these tributary catchments is open to a restricted and tightly controlled amount of timber harvesting. The harvested tributary catchment is ‘taken out of supply’ to ensure that any adverse impact on water quality from logging does not enter the water supply system. One of the consequences of this is increased flow for environmental benefits for the Yarra River.

2.3.1 Armstrong Creek Main

The Armstrong Creek Main catchment is located approximately 85km to the east of Melbourne. The Armstrong Creek Main catchment referred to in this report is defined as the catchment upstream of the gauging station at the weir (399460E, 5834009N), with a catchment area of 39.3km^2. A photo of the Armstrong Creek Main upstream of the gauging station is provided in Figure 2.5.

The elevation within the catchment ranges from 340 to 1390m above sea level. A digital elevation model of the catchment is shown in Figure 2.6.

Figure 2.5. The Armstrong Creek Main, above the gauging station.

A vegetation map of the Armstrong Creek Main catchment, and a table of vegetation abundances are presented in Figure 2.7 and Table 2.3 respectively. The catchment is completely forested, predominantly by *E. regnans*, mixed species forests, *E. delegatensis*, with lesser occurrences of *Acacia dealbata*, rainforest species and *E. nitens*. The geology of the catchment consists of Devonian Rhyodacites in the upper reaches, with Devonian sandstones and siltsones further south towards the catchment outlet, and minor occurrences of Devonian granites and metamorphics in the lower western portion (DSE, 2004). Soils in the higher reaches of the catchment are shallow stony earths, with brown earths in the lower areas.

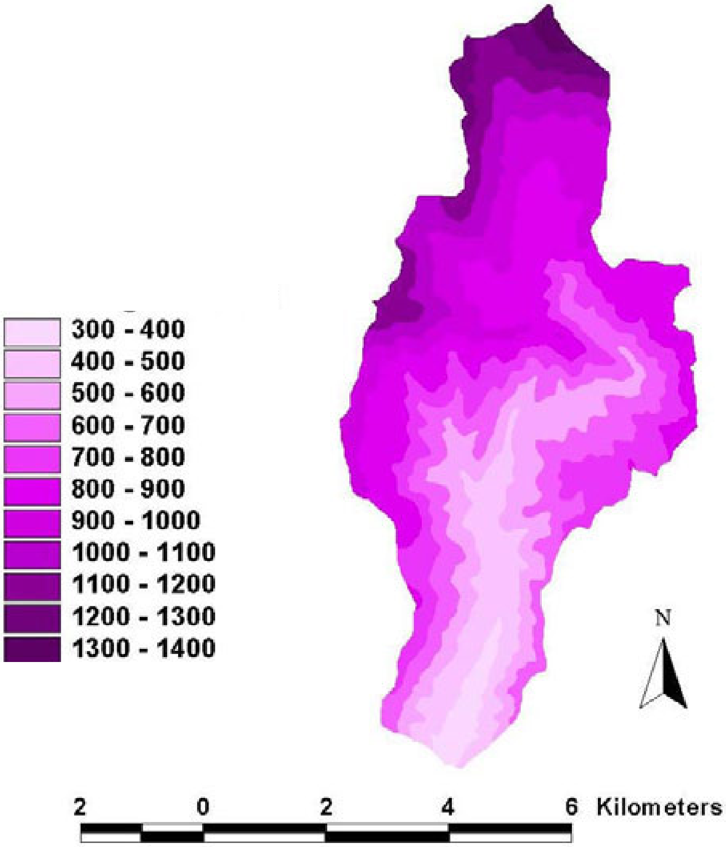

Figure 2.6. Digital elevation model (DEM) in metres (m) of the Armstrong Creek Main catchment.

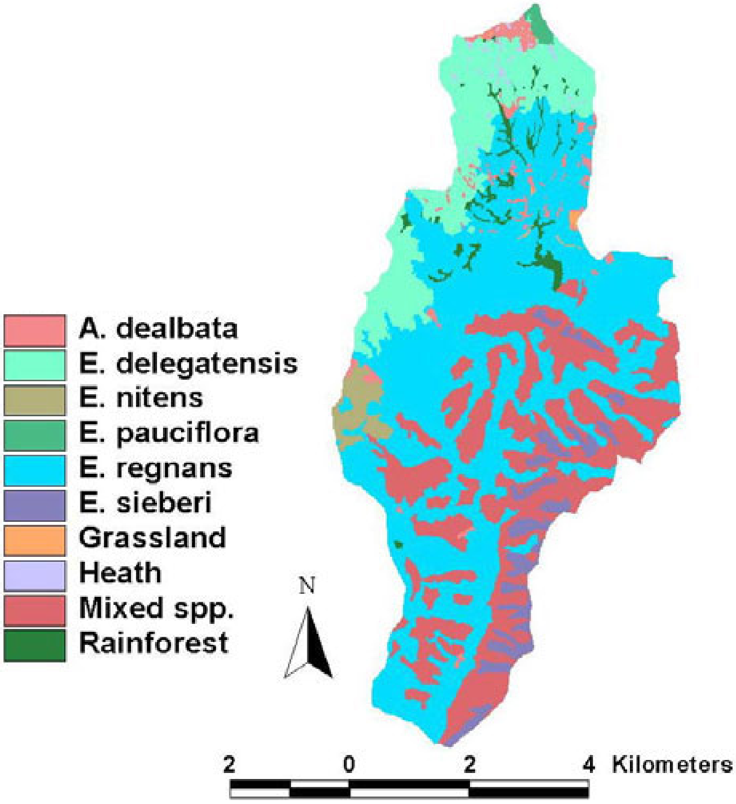

Figure 2.7. Vegetation type map for the Armstrong Creek Main catchment.

Table 2.3. Vegetation type by percentage in the Armstrong Creek Main catchment.

Vegetation type	Percentage
E. regnans	50.3
Mixed spp.	25.4
E. delegatensis	13.0
E. sieberi	4.3
A. dealbata	2.2
Rainforest	2.0
E. nitens	1.9
E. pauciflora	0.43
Heath	0.36
Grassland	0.18

2.3.2 Armstrong Creek East

The Armstrong Creek East catchment is located approximately 86km to the east of Melbourne. The Armstrong Creek East catchment referred to in this report is defined as the catchment upstream of the gauging station above the weir (399774E, 5833737N), with a catchment area of 14.5km^2. A photo of the Armstrong Creek East near the catchment outlet is provided in Figure 2.8.

Figure 2.8. The Amstrong Creek East near the catchment outlet.

The elevation within the catchment ranges from 340 to 850m above sea level. A digital elevation model of the catchment is shown in Figure 2.9. A vegetation map of the Armstrong Creek East catchment, and a table of vegetation abundances are presented in Figure 2.10 and Table 2.4 respectively. The catchment is completely forested, predominantly by mixed species forests, together with *E. regnans* and *E. sieberi*. The geology of the catchment is entirely Devonian sandstones and siltstones (DSE, 2004). The soils in the catchment are predominantly brown earths.

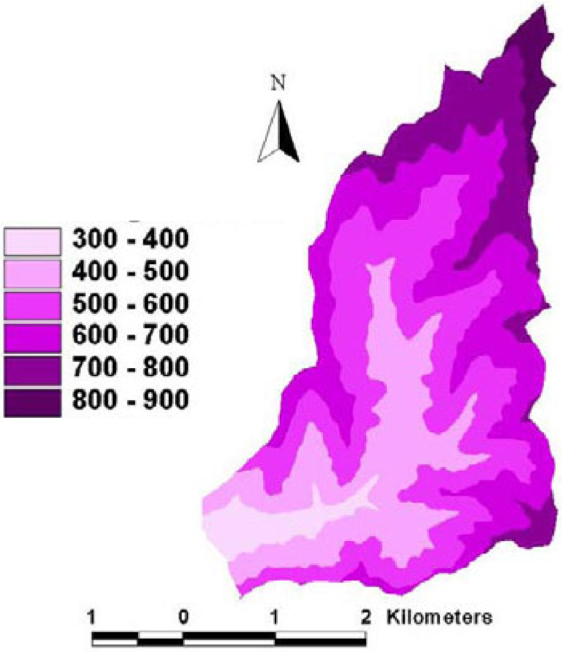

Figure 2.9. Digital elevation model (DEM) in metres (m) of the Armstrong Creek East catchment.

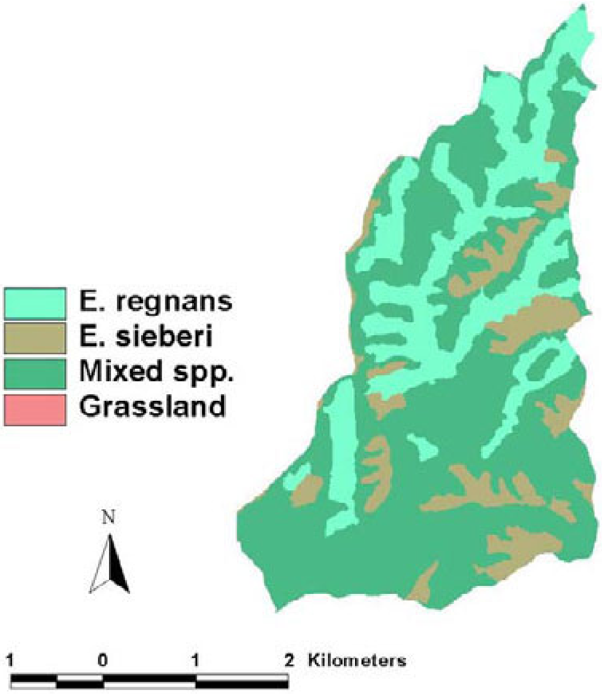

Figure 2.10. Vegetation type map for the Armstrong Creek East catchment.

Table 2.4. Vegetation type by percentage in the Armstrong Creek East catchment.

Vegetation type	Percentage
Mixed spp.	61.5
E. regnans	24.9
E. sieberi	13.6
Grassland	0.004

2.3.3 Cement Creek

The Cement Creek catchment is located approximately 71km to the east of Melbourne. The catchment referred to in this report is defined as that above the gauging station at (389473E, 5825628N), and has a catchment area of 14.3km^2. This is the smallest catchment in this study. A photo of the gauging station on the Cement Creek is provided in Figure 2.11.

Figure 2.11. The gauging station on the Cement Creek.

The elevation within the catchment ranges from 250 to 850m above sea level. A digital elevation model of the catchment is shown in Figure 2.12. A vegetation map of the catchment is provided in Figure 2.13 and a table of vegetation type by percentage is given in Table 2.5. It is predominantly vegetated by *E. regnans*, with an area of *E. nitens* in the north east of the catchment, and Rainforest and *E. delegatensis* in the western part of the catchment. The geology is predominantly Devonian rhyodacites, with Quaternary alluvium in the lower portion near the catchment outlet (DSE, 2004). Soils in the higher reaches of the catchment are friable earths and shallow stony earths, with red earths and brown earths in the lower areas.

Table 2.5. Vegetation type by percentage in the Cement Creek catchment.

Vegetation type	Percentage
E. regnans	79.9
E. nitens	7.3
Rainforest	5.9
E. delegatensis	4.0
A. dealbata	2.6
Heath	0.29

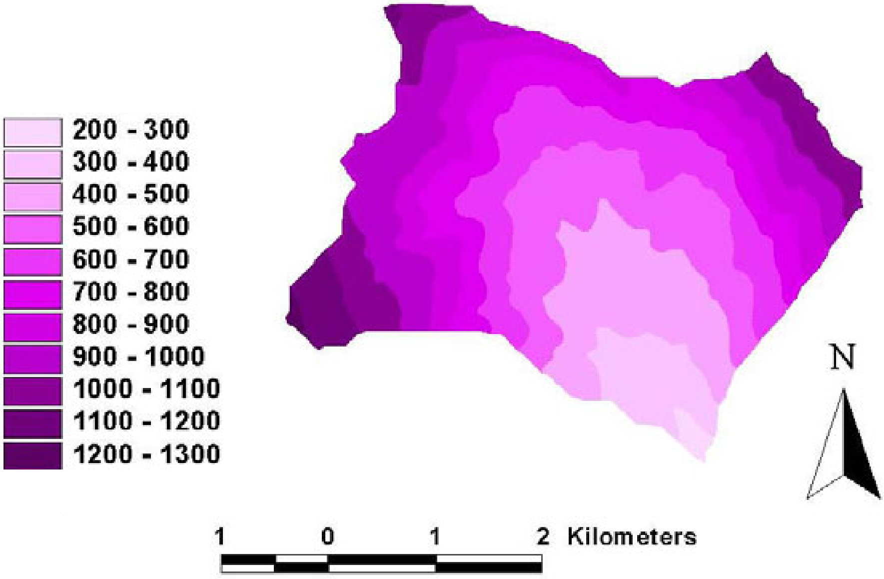

Figure 2.12. Digital elevation model (DEM) in metres (m) of the Cement Creek catchment.

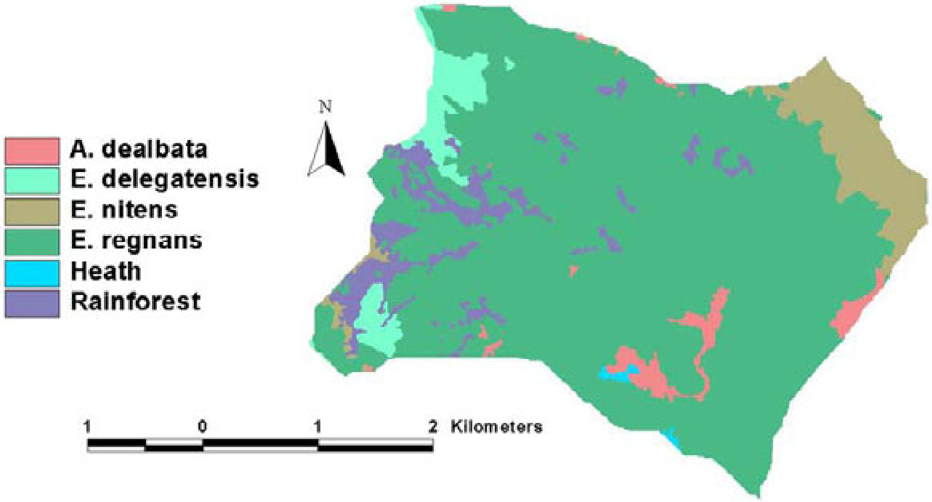

Figure 2.13. Vegetation type map for the Cement Creek catchment.

2.3.4 McMahons Creek

The McMahons Creek catchment is located approximately 85km to the east of Melbourne. The McMahons Creek catchment referred to in this report is defined as the catchment upstream of the gauging station above the weir (401631E, 5824703N), with a catchment area of 39.5km^2. A photo of the McMahons Creek at the gauging station is shown in Figure 2.14.

Figure 2.14. The McMahons Creek at the gauging station.

The elevation within the catchment ranges from 330 to 940m above sea level. A digital elevation model of the catchment is shown in Figure 2.15. A vegetation map of the McMahons Creek catchment, and a table of vegetation type abundances are presented in Figure 2.16 and Table 2.6 respectively. The catchment is completely forested, predominantly by *E. regnans* and mixed species forests, with smaller occurrences of *E. sieberi* and other vegetation types. The geology of the catchment is Devonian granites in the southern half of the catchment, and Devonian sandstones in the north towards the catchment outlet, separated by a band of Devonian metamorphics (DSE, 2004). Soils in the higher reaches of the catchment are red and brown earths, with brown earths in the lower areas.

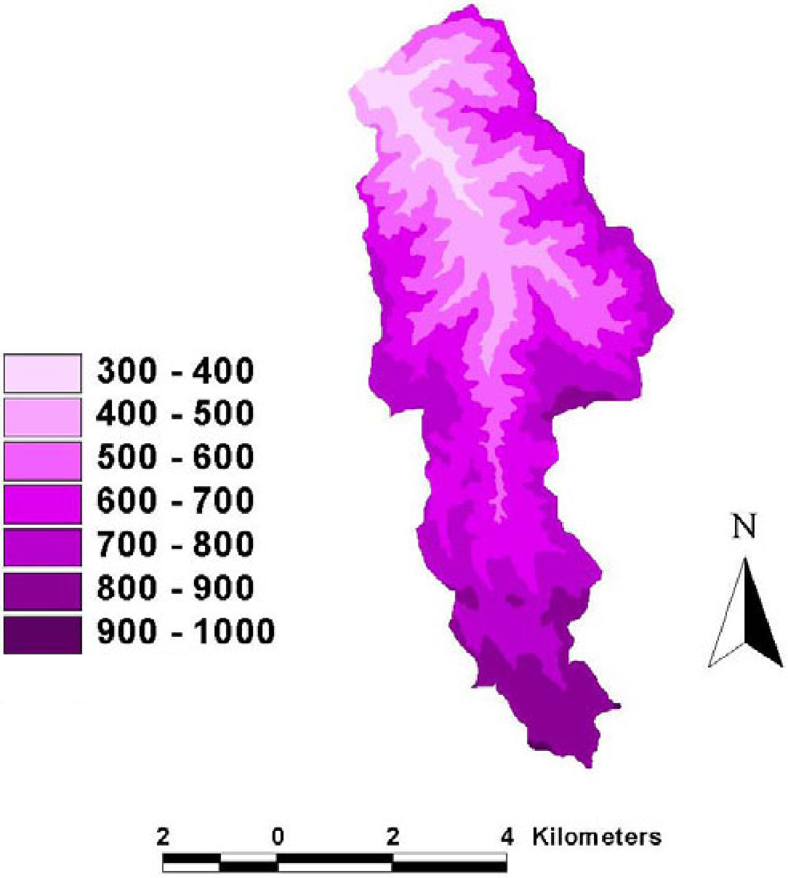

Figure 2.15. Digital elevation model (DEM) in metres (m) of the McMahons Creek catchment.

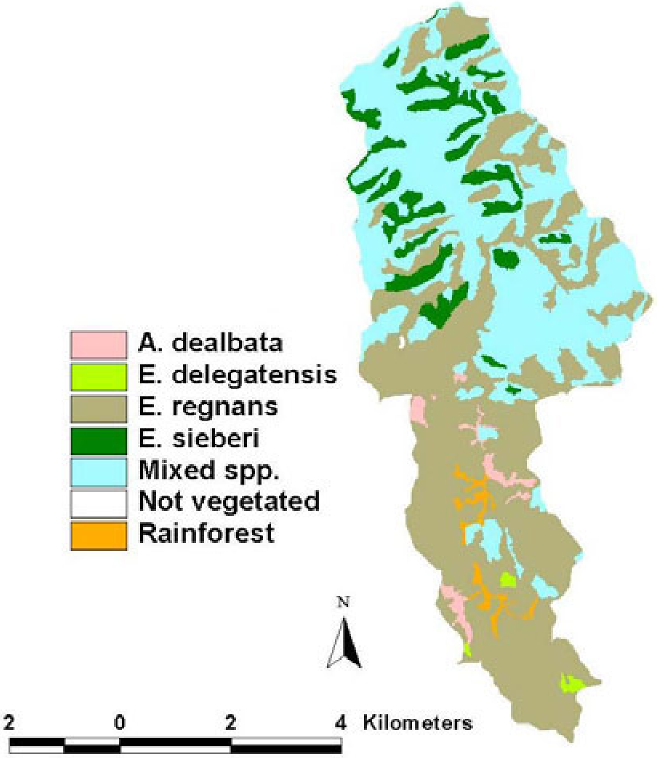

Figure 2.16. Vegetation type map for the McMahons Creek catchment.

Table 2.6. Vegetation type by percentage in the McMahons Creek catchment.

Vegetation type	Percentage
E. regnans	49.3
Mixed spp.	38.6
E. sieberi	8.8
A. dealbata	1.6
Rainforest	1.2
E. delegatensis	0.44
Not vegetated	0.05

2.3.5 Starvation Creek

The Starvation Creek catchment is located approximately 81km to the east of Melbourne. The Starvation Creek catchment referred to in this report is defined as the catchment upstream of the gauging station above the weir (398468E, 5820584N), with a catchment area of 31.3km^2. A photo of Starvation Creek above the gauging station is shown in Figure 2.17.

Figure 2.17. The Starvation Creek above the gauging station.

The elevation within the catchment ranges from 320 to 940m above sea level. A digital elevation model of the catchment is shown in Figure 2.18. A vegetation map of the Starvation Creek catchment, and a table of vegetation abundances are presented in Figure 2.19 and Table 2.7 respectively. The catchment is completely forested, predominantly by *E. regnans* and mixed species forests, with smaller occurrences of

E. sieberi, rainforest, and other vegetation types. The geology of the catchment is primarily Devonian granites, which occupy the southern two thirds of the catchment, with Devonian metamorphics, and Devonian sandstones in the northern tip of the catchment (DSE, 2004). Soils in the higher reaches of the catchment are predominantly red and brown earths, with some brown earths in the lower areas.

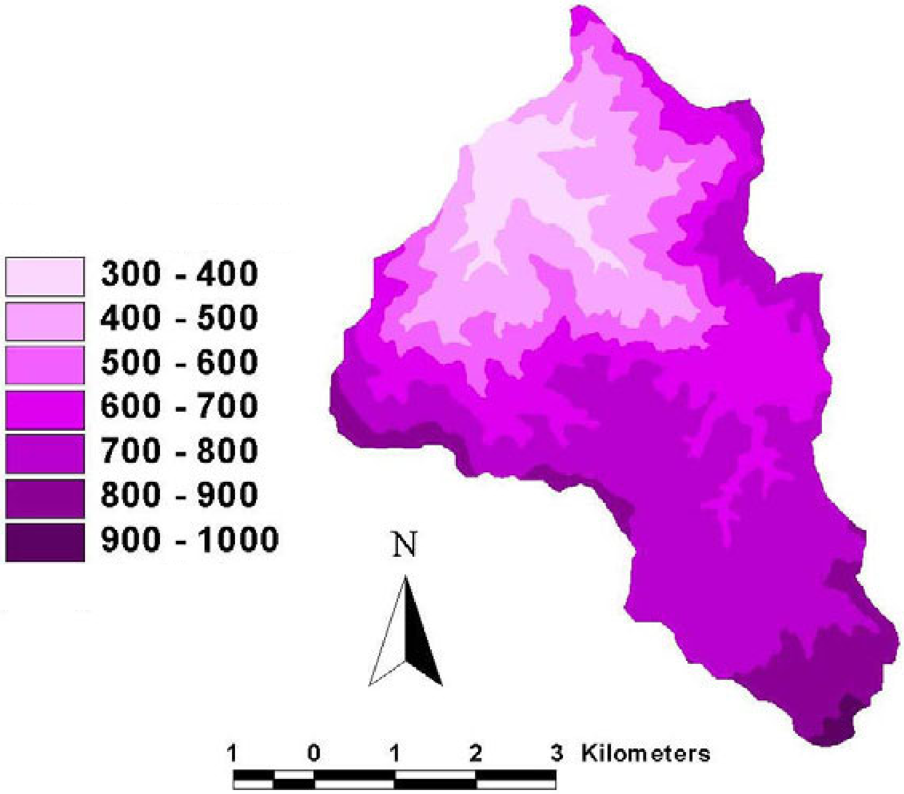

Figure 2.18. Digital elevation model (DEM) in metres (m) of the Starvation Creek catchment.

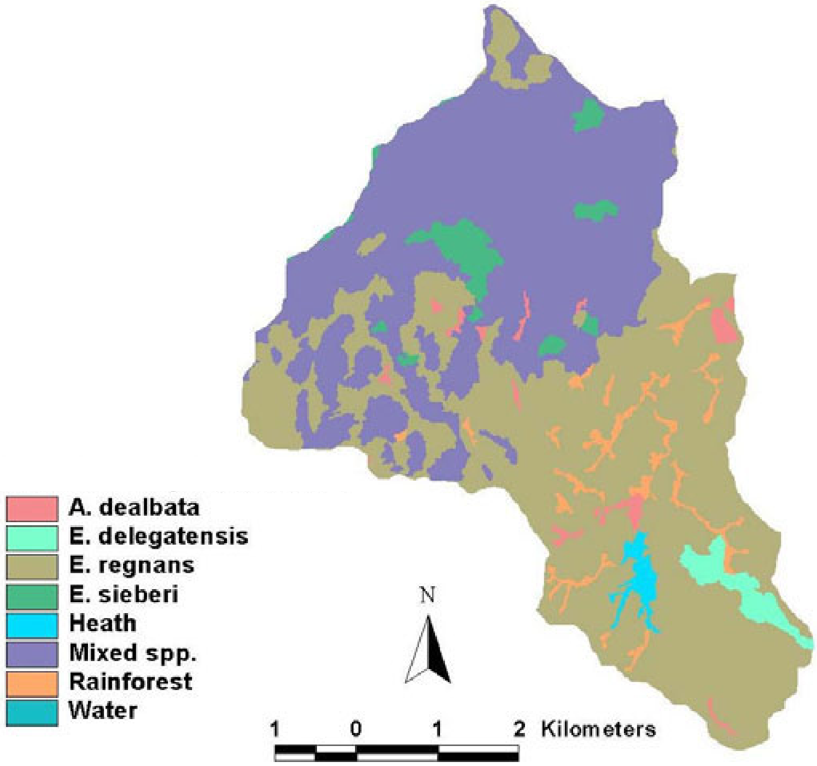

Figure 2.19. Vegetation type map for the Starvation Creek catchment.

Table 2.7. Vegetation type by percentage in the Starvation Creek catchment.

Vegetation type	Percentage
E. regnans	49.5
Mixed spp.	41.1
E. sieberi	2.9
Rainforest	2.6
E. delegatensis	1.7
A. dealbata	1.4
Heath	0.86
Water	0.002

2.4 Tarago

The Tarago catchment is located approximately 85km to the east of Melbourne. The Tarago catchment referred to in this report is defined as the catchment above the dam wall (406552E, 5791373N) with a catchment area of 112.9km^2. In the absence of any observed flow data at the dam wall, the Macaque model for the catchment was calibrated against observed streamflow record at the gauging station above the dam wall on the Tarago River at Neerim (at Elton Rd; station number 228206) (406363E, 5797767N) with a catchment area of 78.9km^2. A photo of the gauging station at Elton Rd near Neerim is shown in Figure 2.20.

Figure 2.20. The gauging station on the Tarago River @ Neerim.

The elevation within the catchment ranges from 160 to 890m above sea level. A digital elevation model of the catchment is shown in Figure 2.21. A vegetation map of the Tarago catchment, and a table of vegetation type abundances are presented in Figure 2.22 and Table 2.8 respectively. The catchment is predominantly forested, with 20% of the area used for agricultural landuses. The forested area is predominantly *E. regnans* and mixed species forests, with smaller occurrences of *E. sieberi*, and other vegetation types.

The geology of the catchment is predominantly Devonian granites, the spatial extent of which corresponds to the forested area. The agricultural region along the eastern border of the catchment includes Tertiary volcanics, together with some Devonian metamorphics and Silurian-Devonian sediments (DSE, 2004). Soils within the catchment are predominantly red and brown earths in the higher reaches, which correspond to the forested areas. The lower areas used for agriculture are predominantly red friable earths with some yellow duplex soils.

Water is extracted at the Pedersen Weir (which is about 5km upstream of the gauging station at Neerim) and routed to the Warragul Water Treatment Plant, from where it supplies treated water to the towns of Warragul, Drouin, Nilma, Darnum, Buln Buln and Rokeby. The Pedersen Weir was commissioned in December 1963, but extraction data only goes back to July 1996 due to water authority amalgamations and lost data. As a result, the streamflow data between December 1963 and June 1996 cannot be used for model calibration purposes. Water is also extracted through the Tarago Main Race (TMR) just upstream of the gauging station at Tarago River at Neerim. Monthly extractions from Pedersen Weir and from the TMR were added to the streamflow recorded at Tarago River at Neerim for calibration purposes.

Construction of the Tarago Reservoir commenced in 1966 and was completed in 1969. Water from the reservoir was once used to supply the Mornington Peninsula and West Gippsland, however, the Reservoir was taken offline in 1994 after occurrences of blue-green algal blooms.

The algal blooms in the Tarago Reservoir are thought to be due to the surface erosion processes of the naturally phosphorous rich basalt soils of the catchment. Phosphorous is the limiting nutrient for algal growth in the Tarago Reservoir. Sediment trace studies have revealed that the surface erosion processes is caused from both the activities in the forested western catchment (timber harvesting and roads etc.) and the agricultural activities in the eastern catchment (Dyer, 1998).

In June 2005, the Minister for Water announced that Tarago Reservoir would be reconnected into the Melbourne system by 2011 to help protect Melbourne’s supplies from the impact of climate change. Potential water quality issues will be addressed by undertaking catchment management works and by building a water treatment plant near the Reservoir, with a view to providing an additional 21,000 ML of water per annum.

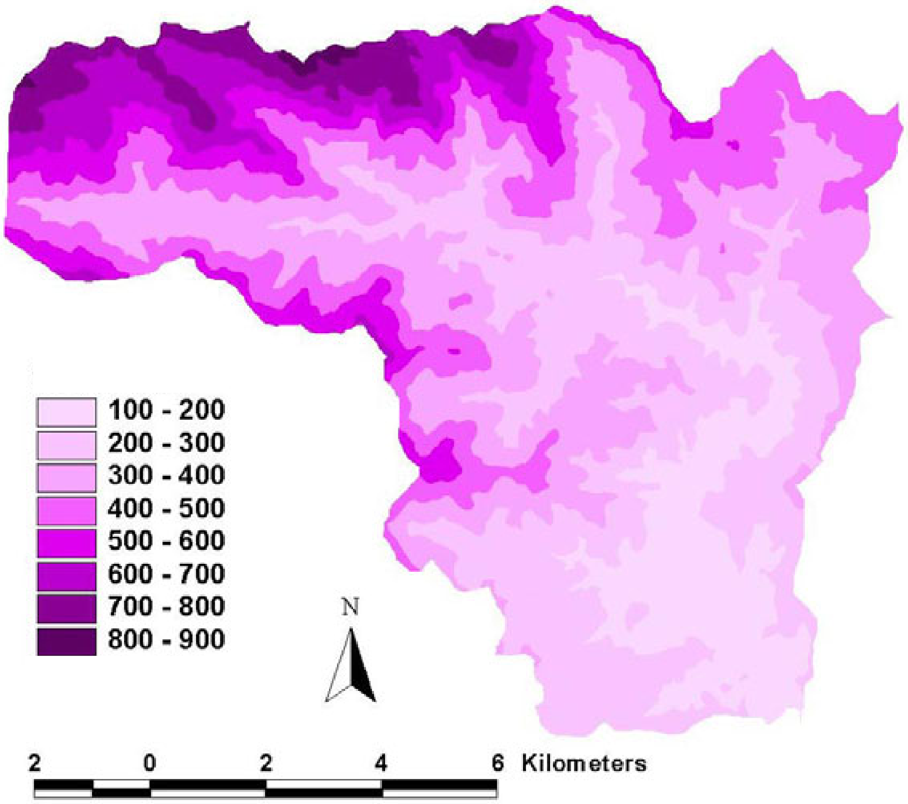

Figure 2.21. Digital elevation model (DEM) in metres (m) of the Tarago catchment upsteam of the dam wall.

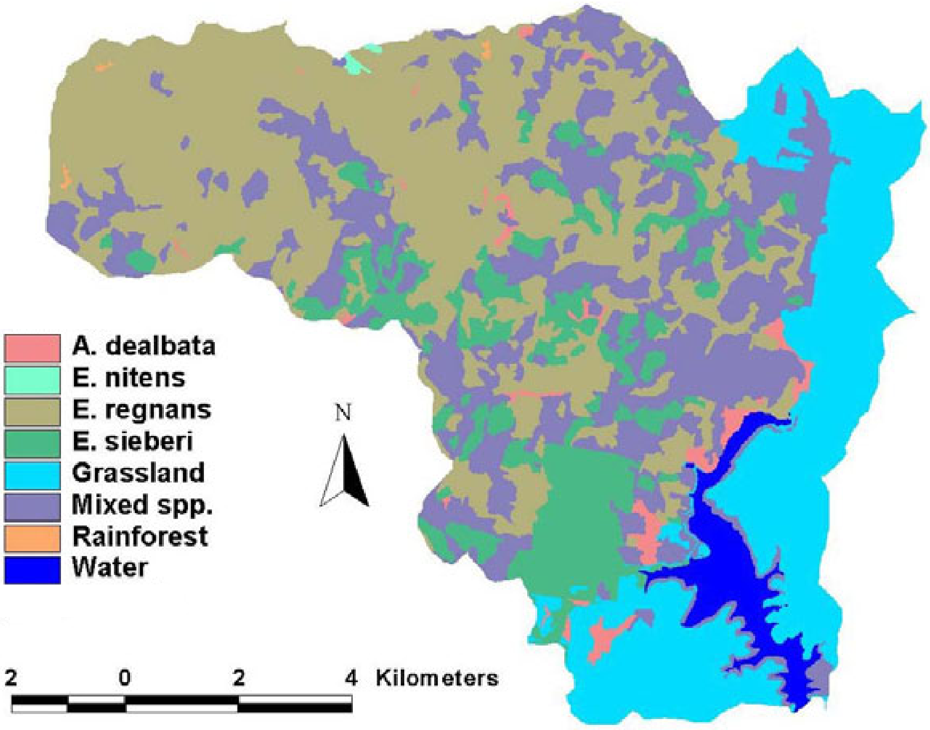

Figure 2.22. Vegetation type map for the Tarago catchment.

Table 2.8. Vegetation type by percentage in the Tarago catchment.

Vegetation type	Percentage
E. regnans	37.5
Mixed spp.	25.5
Grassland	20.0
E. sieberi	12.1
Water	3.1
A. dealbata	1.6
E. nitens	0.10
Rainforest	0.08

2.5 Bunyip

The Bunyip catchment is located approximately 69km to the east of Melbourne. The Bunyip catchment referred to in this report is defined as the gauging station at the headworks (389866E, 5800430N), with a catchment area of 39.4km^2. A photo of the Bunyip River just below the headworks is shown in Figure 2.23.

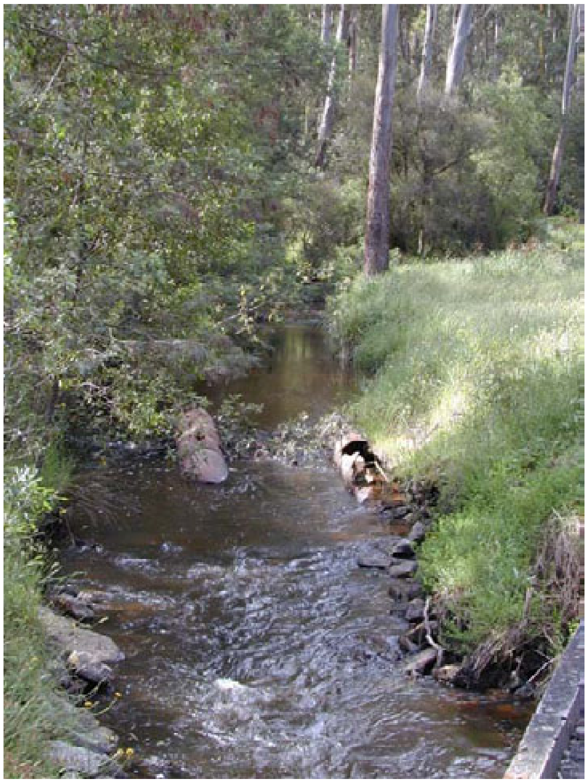

Figure 2.23. The Bunyip River downstream of the headworks.

The elevation within the catchment ranges from 130 to 840m above sea level. A digital elevation model of the catchment is shown in Figure 2.24. A vegetation map of the Bunyip catchment, and a table of vegetation type abundances are presented in Figure 2.25 and Table 2.9 respectively. The catchment is completely forested, and is predominantly *E. regnans* and mixed species forests, with smaller occurrences of *A. dealbata*, *E. sieberi*, and other vegetation types. The geology of the catchment is entirely Devonian granites (DSE, 2004). The soils in the catchment are red and brown earths.

Actual gauged flow data exists for the Bunyip Main Race (BMR) from January 1948 until June 1987. Flow data between June 1987 and September 1992 were supplied by the Mornington Peninsula and District Water Board (MPDWB), but it is unclear whether this is gauged data or a single daily read value. Flow data from September 1992 to December 2004 were collected by Melbourne Water's Integrated Control Centre (ICC) at Brooklyn. However, field visits to the Bunyip catchment indicated that there is flow diverted along the BMR for private use. This flow was ungauged and occurred from June 1987 onwards, and therefore only flow data up until May 1987 could be used for model calibration purposes.

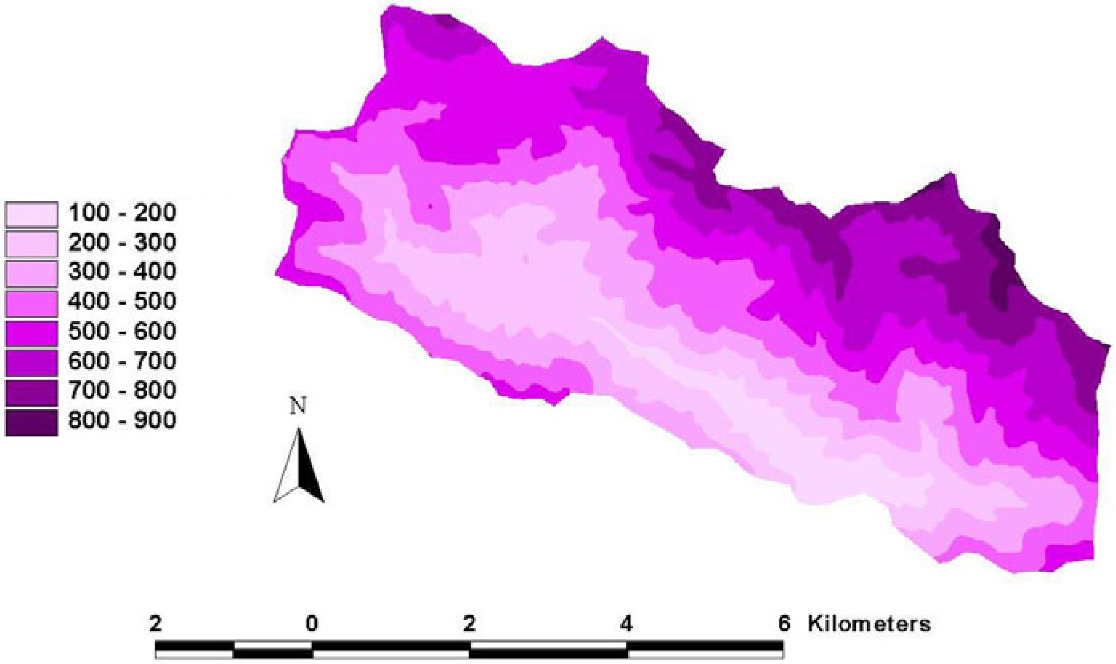

Figure 2.24. Digital elevation model (DEM) in metres (m) of the Bunyip catchment.

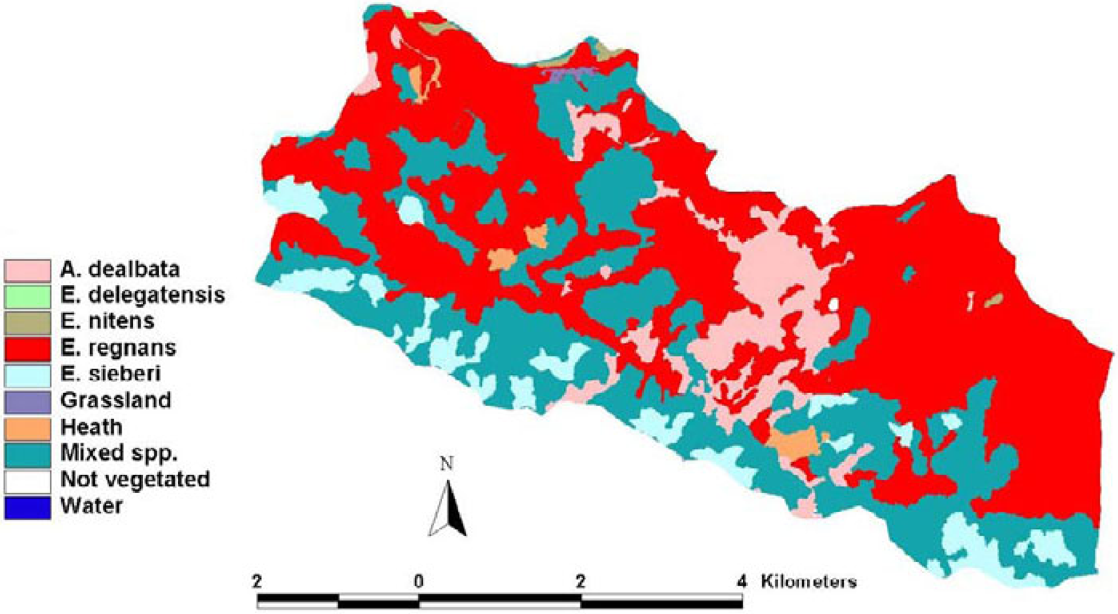

Figure 2.25. Vegetation type map for the Bunyip catchment.

Table 2.9. Vegetation type by percentage in the Bunyip catchment.

Vegetation type	Percentage
E. regnans	52.8
Mixed spp.	30.4
A. dealbata	8.6
E. sieberi	6.6
Heath	1.0
E. nitens	0.38
Grassland	0.16
Not vegetated	0.05
E. delegatensis	0.02
Water	0.002

3. Overview of Macaque

3.1 Introduction

Macaque is a physically-based catchment model, and aims to represent the dominant, real physical processes occurring within a catchment using mathematical equations. It was developed by Watson (1999), with summaries provided in Watson *et al*. (1998 & 1999a).

Such physically-based models may be used for simulating hydrologic processes and predicting resultant water balances where measurements of water yield are not available, and for predicting the impact of future changes in vegetation cover on catchment water balances.

A brief description of the structure of the Macaque model and its data requirements are presented below.

3.2 Model structure

The Macaque model was originally developed by Watson (1999), with summaries given by Watson *et al*. 1998 & 1999a. It was originally developed using the Tarsier framework and was written in C++. Recently it has been translated into C#.NET using the TIME (The Invisible Modelling Environment). The major features developed for the first release of Macaque as a Cooperative Research Centre for Catchment Hydrology Toolkit product included;

- a “Configuration Wizard” (a number of pages for gathering data, defining catchment boundaries and setting parameters)
- a main screen for visualisation of data
- a data base persistence layer for storing and retrieving configurations
- the ability to run configured simulations
- the ability to select and record whole of catchment variables
- a number of statistical tools (bivariate and univariate statistics) for manual calibration, and
- a screen for changing model parameters.

Wherever possible, model parameters are assigned values based on direct measurements of physical properties within the respective catchment, or reasonable and appropriate values taken from the literature. A few parameters, particularly those relating to soil properties, remain for calibration against observed water yield. Such parameters are unlikely to change with forest disturbance. Once they are calibrated for a given catchment under known disturbance regimes, they are considered to be robust. Therefore, assuming a stationary climate, model predictions are considered to be valid when future disturbance regimes are simulated. Catchment processes and therefore model parameters may change under a climate change scenario.

The catchment is discretised spatially into hillslopes, and hillslopes into smaller areas known as elementary spatial units (ESUs). Each ESU is modelled separately, and individual ESUs are linked together by subsurface water flow pathways. Hillslopes are linked together by a stream network, which sums the flow from all the hillslopes to get the total catchment flow. The model runs on a daily timestep and requires a daily time series of precipitation and maximum and minimum temperature as input.

Within each ESU, two layers of vegetation are represented: canopy and understorey. Precipitation interception and throughfall is modeled for both these layers. Solar radiation is also propagated through, and absorbed by these layers. The Penman-Monteith equation (Monteith & Unsworth, 1990) is used in the model to calculate evapotranspiration (ET) from each of the layers, as well as to calculate evaporation from the soil.

Each ESU has two soil zones, representing the unsaturated and saturated soil respectively. The interface between these two zones is the watertable, which may move upwards and downwards in response to vertical water movement, and to inflows and outflows from and to ESUs above and below, within the hillslope. The Van Genuchten model (Van Genunchten, 1980 and Rawls *et al*. 1993) is used to calculate recharge from the unsaturated to the saturated zone. Darcy's Law (Shaw, 1994) is used to move saturated water laterally within hillslopes using explicit transfers of water between neighbouring ESUs. This last step is a new development from the original model presented by Watson (1999). This new scheme was tested by Peel *et al*. (2001) in calibrations of Macaque on eight large, diverse catchments from around Australia and is described in Watson *et al*. (2001).

A detailed climate sub-model is used to convert precipitation and temperature range inputs into required climate variables such as radiation and humidity for the estimation of evapotranspiration.

Predictions of water yield are sensitive to climate, vegetation water use, the amount of water stored within the soil, and the rate at which this water moves into and out of the soil and into the streams. Therefore, spatial changes in climate, vegetation, soil, and topography cause changes in water yield.

Changes in forest type and age are represented by changes in leaf area index (LAI) and leaf conductance to water vapour. The leaf area index is defined as the green leaf area (m^2) of a tree per unit ground area (m^2), and as such is a dimensionless parameter. As in most physically based models, LAI is a major control of all evapotranspiration systems, influencing leaf conductance, canopy conductance, radiation interception, and precipitation interception. Leaf conductance describes the relationship between sapwood area (the cross sectional area of water conducting tissue in the tree stem) per unit LAI. There is evidence to suggest that mean maximum leaf conductance in *E. regnans* forests declines markedly with age (see Watson, 1999). This is suggested by evidence that a) stand sapwood area (SA) per unit LAI declines with age; and, b) that mean daily sapwood velocity is constant with age.

Within macaque, the LAI and leaf conductance are specified to the model as a series of LAI with age and conductance with age relationships for each forest type (e.g. Mountain Ash, Mixed Species, Rainforest, Heath).

3.3 Model development

For the tasks outlined in this study to be achieved, further development of Macaque was required. The following developments were made to include the ability to:

- Create spatial maps of selected variables accumulated over the simulation period. This enables users to visualise the spatial variance of a particular variable or parameter. Currently, variables for each unit are accumulated over the entire simulation period, however, further development would allow for spatial maps to be produced for selected time periods (weekly, monthly, annually etc).

- Record temporal variables for each elementary spatial unit (ESU) at both daily and annual time steps. This enables users to explore a catchment at the finest resolution of modelling (i.e. ESU). ESUs can be identified using the conceptual view (in the "Output Manager") or by selecting them on an esuMap contained in the "Configuration Data" list in the "Configuration Manager".

- Group and filter elementary spatial units based on parameter values. When performing further catchment analysis it was useful to group ESUs based on similar parameter values. Grouping of ESUs with the same dominant vegetation type is achieved by checking the "Group by" box and selecting "p_canopy_species" from the ESU parameter list. Once the model has run, the outputs are grouped in a specified folder based on the selected parameter.

- Identify and filter time series. The "Bulk Time Series Tester" is a dedicated tool for identifying/filtering outputs (Time series) that do not match a condition ($x_i - x_{i-1} <$ threshold level). The number of times this condition is broken is recorded and if the number exceeds a set value, then the time series is considered unsuitable for further analysis (see Section 7.2).

3.4 Data requirements

Macaque requires several spatial and temporal data sets. These requirements include topographic, vegetation and climate data, details for which are outlined below.

3.4.1 Topographic

A digital elevation model (DEM) is required to define catchment boundaries and to delineate hillslopes and ESUs. It is also the source of topographic parameters, such as slope, aspect, and elevation, which are used to compute solar radiation in addition to other inputs. The resolution of the DEM used is constrained by data availability, as well as the catchment size and the speed of the computer that will be running the model.

A 10m DEM was supplied by DSE that was then resampled as a 40m DEM and used in Macaque. Macaque creates a stream network based on the DEM and stream threshold. The stream threshold can be increased or decreased to regenerate the stream network map with less or more detail respectively. The value for stream threshold will also effect the number of ESUs defined by Macaque in the resulting ESU map of the catchment. A lower stream threshold will lead to a greater number of (smaller in average area) ESUs.

For each catchment, the respective DEM was analysed to create a stream network and to delineate the catchment boundary, hillslopes and ESUs. Each DEM was analysed in the following manner. Pits and flats in the DEM were removed using the algorithm of Watson (1999). A stream network was calculated and hillslopes identified as the area upslope of each segment of the network. A topographic index (Beven *et al*. 1995) was calculated at all points in the DEM. This index increases as one moves down the hillslope, and decreases as the terrain steepens. Areas of similar topographic index are then grouped together as single ESUs within each hillslope. A location for the catchment outlet is selected and all hillslopes and ESUs upstream of this point are included in that catchment.

3.4.2 Vegetation

Macaque requires information on vegetation type and vegetation age. Maps of forest type and age were produced from several sources which required a substantial amount of processing and classification. Since the application of Macaque to the Thomson catchment by Peel *et al*. (2000), the State Forest Resource Inventory (SFRI) dataset for forest type and age has become available. The SFRI is the first comprehensive, standardised statement of the State's native forest resources, and it represents a significant improvement in the accuracy of vegetation data used in Macaque.

The State Forest Resource Inventory (SFRI) was undertaken for all areas of state forest for the majority of Victoria. This inventory covers most of the study catchments, and other sources were consulted where SFRI data were not available. SFRI data were used except in the following cases.

- The north-west of the Cement Creek catchment (National Park) which required the use of the Forest25 dataset originally collected in the early 1980s.

- The National Park section of the Armstrong catchment covering approximately 860ha, was not covered by SFRI data, and two other datasets were consulted i) the 1979 ash survey and ii) the Forest 25Leadbeaters Possum/Old growth mapping. The former dataset was not available in GIS format, so it was not used directly, but was examined and used for cross-referencing.
- The National Park areas of the Thomson catchment were not mapped by SFRI. Detailed mapping of these areas in the Baw Baws was completed by Ian Roberts for the Department of Sustainability and Environment. This mapping provided coverage of areas not mapped by SFRI and also provided detail for some areas of non-eucalypt within the SFRI mapping.
- Private property areas in the Tarago catchment were not mapped by SFRI, but do include areas of forest. These were mapped using aerial photography and digital images.

Furthermore, SFRI did not provide detail on areas of recently harvested stands or low productivity mixed species forest. This detail was included by examining current and historic aerial photography and digital imagery.

The data were amalgamated to provide a dataset with the vegetation types, *E. delegatensis*, *E. regnans*, *E. nitens*, Rainforest, *Leptospermum* species, *E. pauciflora*, Grassland, Nil vegetation, Heath, *E. sieberi*, mixed species). The resulting layers of vegetation type for each catchment are provided in Section 2.

Two disturbance layers were created from the data. This was considered adequate in terms of describing catchment disturbance over the simulation period. The first layer represents the base layer, and each grid cell contains the year that vegetation type commenced growing (i.e. after the previous disturbance). For example, a grid cell with the year 1900 represents vegetation that germinated in 1900, which would be 54 years old for a model simulation starting in 1954. Information on vegetation age required for this layer was determined by local records, historic aerial photos, or from logical assumption. An example of the vegetation base age layer for the Thomson catchment is shown in Figure 3.1.

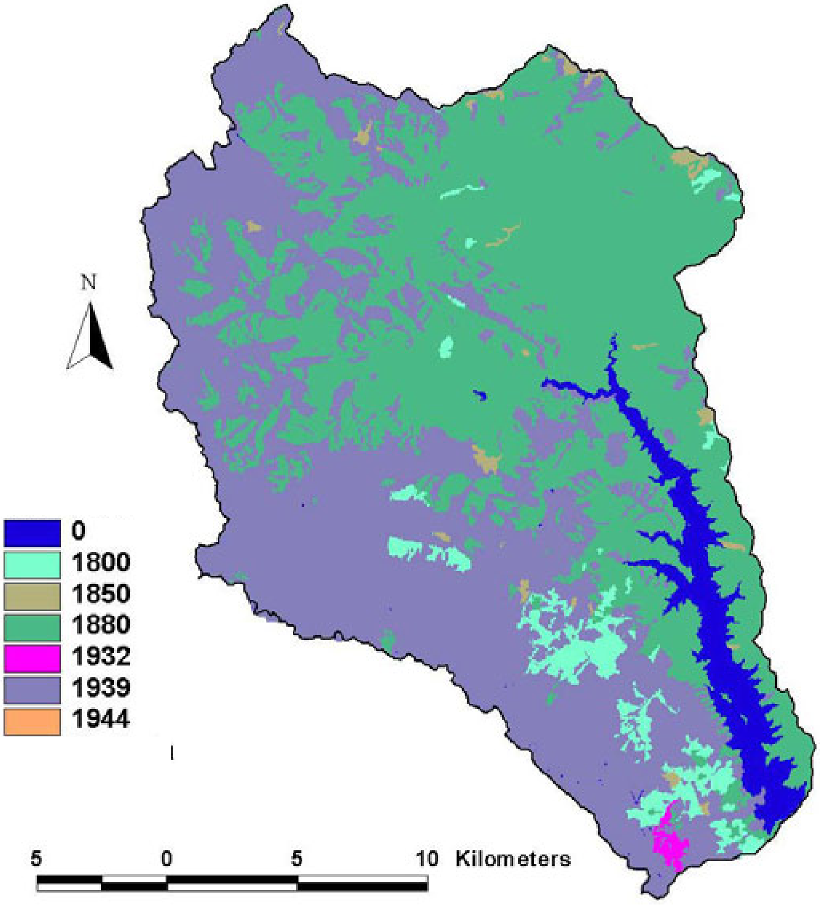

Figure 3.1. Vegetation base age (year) layer for the Thomson catchment.

Forest disturbance by fire and/or timber harvesting activities has altered vegetation age in all of the study catchments. An additional age layer includes a year in each grid cell relating to a disturbance (if applicable). For example, if a grid cell contained a year value of 1980, then the vegetation will undergo disturbance in 1980, and commence regrowing afterwards. The process of assigning years to indicate vegetation age required regrouping of some existing classifications. For example, uneven-aged forest must be assigned a single age class, so this was determined by the dominant age class of that forest. An example of the vegetation disturbance age layer for the Thomson catchment is shown in Figure 3.2.

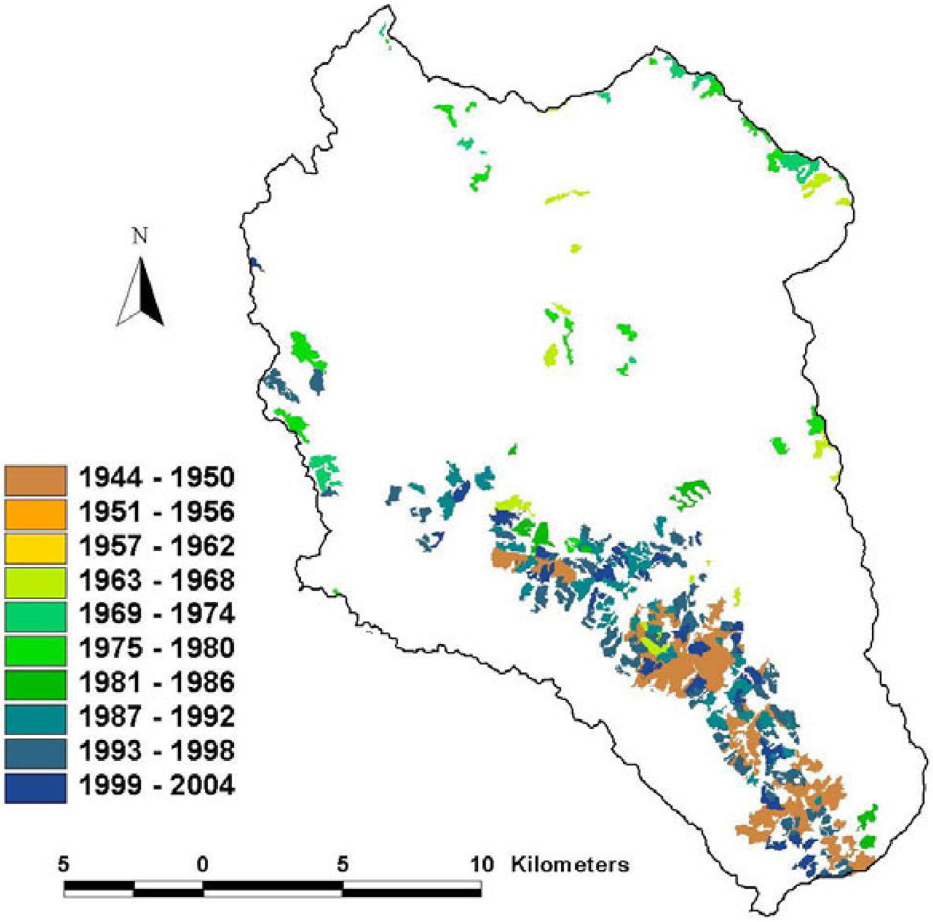

Figure 3.2. Vegetation disturbance age (year) map for the Thomson catchment. Note that for the purposes of presentation, years within a given range have been colour coded with the same colour. The data layer itself contains cells with a unique year in that cell where a disturbance occurred. Blank cells (no data) indicate cells in which no disturbance has occurred.

Macaque also requires information on long-term vegetation development. These are supplied in the form of curves for each species representing changes in LAI and leaf conductance with forest age. In Macaque, LAI of the canopy and understory is modelled. This is described in further detail by Watson (1999). For the Ash-type species, *E. regnans*, *E. nitens*, and *E. delegatensis*, canopy LAI is predicted using the curves developed from experimental data. For all other species, canopy LAI is set to be half of the total LAI estimated from remote sensing techniques. This is loosely based on the ratio between canopy and total LAI in *E. regnans* forests between about 50 and 100 years of age. Understorey LAI is then estimated as the difference between total and canopy LAI.

Relationships between forest age and LAI and maximum leaf conductance for *E. regnans* are well known (Watson, 1999, Watson *et al.*, 1999b and Vertessy *et al.*, 2000). The LAI curve for *E. regnans* to 250 years of age as represented in Macaque is shown in Figure 3.3. The same relationships are assumed to hold for *E. nitens*. The maximum LAI for *E. delegatensis* is assumed to be 0.3 lower than that of *E. regnans* and *E. nitens*. Following the work of Roberts *et al*. (2001) a relationship between forest age and maximum leaf conductance is assumed to hold for all eucalypt species.

For non-ash eucalypts and non-eucalypts the long-term LAI patterns are less well understood, but were assumed to have constant LAI, following a rapid initial increase from zero in the first 5 to 10 years following disturbance (Peel *et al*., 2000). The LAI curve for mixed species vegetation to 250 years of age as represented in Macaque is also shown in Figure 3.3. This is a fairly significant assumption, and is based on limited evidence. Table 3.1 summarises the LAI and leaf conductance relationships adopted for each vegetation type used in this study.

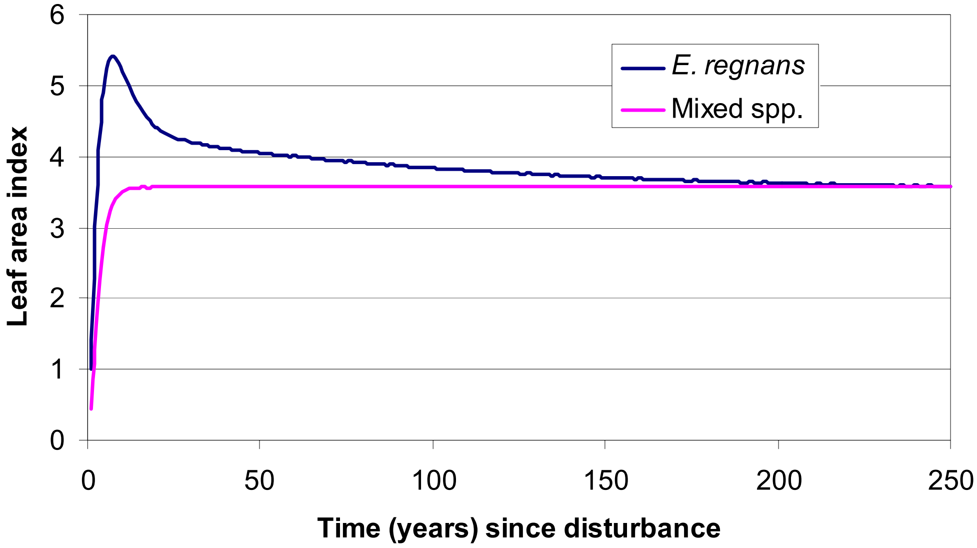

Figure 3.3. Annual LAI with age curve after disturbance for *E. regnans* and for mixed species.

Table 3.1. Long-term trends in leaf area index (LAI) and maximum leaf conductance assumed for the vegetation types present in the catchments in this study.

Forest type	**LAI curve type**	**Maximum LAI**	**Long term LAI**	**Leaf conductance curve type**
Acacia dealbata	Constant*	3.91	3.91	Watson (1999)[3]
E. delegatensis	Watson (1999)[2]	5.7	3.2	Watson (1999)[3]
E. nitens	Watson (1999)[1]	6.0	3.5	Watson (1999)[3]
E. pauciflora	Constant*	2.5	2.5	Watson (1999)[3]
E. regnans	Watson (1999)[1]	6.0	3.5	Watson (1999)[3]
E. sieberi	Constant*	2.94	2.94	Watson (1999)[3]
Mixed spp.	Constant*	3.56	3.56	Watson (1999)[3]
Rainforest	Constant*	3.77	3.77	Watson (1999)[3]
Heath	Constant*	2.50	2.50	Watson (1999)[3]
Leptospermum spp.	Constant*	3.35	3.35	Watson (1999)[3]
Grassland	Constant*	1.50	1.50	Watson (1999)[3]
'Not vegetated'	Constant*	3.15	3.15	Watson (1999)[3]
Water	Constant	0	0	Watson (1999)[3]

* Constant after first 5 to 10 years after establishment; [1]Watson (1999), Equation 8.45; [2]Watson (1999), Equation 8.45. Same as [1] but with LAI lower by 0.3; [3]Watson (1999), Equation 11.1.

3.4.3 Precipitation

The Macaque model requires an estimate of precipitation at each ESU for every day. Observed daily precipitation values are not available at every ESU, and so a method of producing estimates of daily precipitation at each ESU is required. Watson (1999) initially used the mean monthly precipitation index (MMPI) method. The MMPI method was compared to a more recently developed multiple linear regression (MLR) method by Peel *et al.* (2000). They discovered that more of the precipitation variability, which drives streamflow variability, was being captured by the MLR method than by the MMPI method, and concluded that the MLR method was an improvement over the MMPI method. In general they discovered that model predictions improved by about 10% when using the MLR method. The MLR method was adopted for this study.

The MLR method is based on a multiple linear regression of total monthly precipitation at many stations in and around the catchment, and relates this to monthly precipitation at a small number of base stations. The base stations are selected for their long record lengths, and to provide adequate spatial distribution in and around the catchment. The location and elevation of each precipitation station is known, and a three dimensional spline can be applied to interpolate the MLR coefficients across the entire catchment. This results in a number of coefficient maps (one for each base station) representing the MLR coefficient at all locations.

As the model runs, daily rainfall at the base stations is then related to rainfall at each ESU in the whole catchment using the coefficient maps. Three base stations were used for the Thomson catchment, whereas smaller catchment size and station availability led to two base stations being used for the other catchments in this study.

3.4.4 Temperature

Daily maximum and minimum temperature data are required for each ESU. Daily temperature data are generally only available for a few points within the catchment, and therefore a method of estimating maximum and minimum temperatures across the entire catchment is required. The method described by Watson (1999) was used in this study. Here, elevation-based lapse rates are used to calculate maximum and minimum temperatures at each ESU. These temperatures are calculated relative to the base station using the difference in elevation between the ESU and base station. The temperature at a given ESU was calculated using Equation 1.

$$T_{ESU} = T_{BS} + \left(\Gamma_X x \Delta_{Elev}\right) \tag{1}$$

Where T_{ESU} represents the temperature at an ESU (°C), T_{BS} represents the temperature at the base station (°C), Γ_X represents the lapse rate (either for maximum or minimum temperature (°Cm^{-1}) and Δ_{Elev} represents the change in elevation (m). This equation was applied for both maximum and minimum temperature at each ESU. Identical lapse rates of -0.006 °Cm^{-1} were used for all catchments after Watson (1999).

Peel *et al*. (2000) noted that systematic temperature variation occurred within the Thomson catchment that was not fully represented by the simple fixed lapse rate model. Some seasonal dependence was indicated. However, a superior model incorporating such dependencies could not be developed and tested within the time frame of the present study.

Although several temperature stations were available close to some of the catchments, the periods of record were insufficient to meet our long-term modelling requirements. Temperature data for the catchments in this study were obtained from the Bureau of Meteorology. The data from the closest station with long-term temperature data were used. Data from East Sale Airport (station number 085072) were used for the Thomson catchment, and data from Melbourne (station number 086071) were used for the other catchments. The lack of local temperature data of adequate length to facilitate long-term simulations is a severe limitation in forested areas.

3.5 Fixed parameters

Macaque uses numerous parameters that are fixed in space and time, which are described in detail by Watson (1999). Parameter names and values used for model simulations in this study are listed in Table 3.2 for reference.

Table 3.2. Macaque model parameters and values used for this report.

Model parameter name	Fixed value	Comments
p_elevation	variable	From DEM map data
p_sin_aspect	variable	From DEM map data
p_cos_aspect	variable	From DEM map data
p_slope	variable	From DEM map data
p_mean_monthly_precipitation_index	variable	From MMPI map data
p_precipitation_scalar	variable	Calibration parameter
p_precipitation_coeff_0	variable	From MLR map data
p_precipitation_coeff_1	variable	From MLR map data
p_precipitation_coeff_2	variable	From MLR map data
p_precipitation_coeff_3	variable	From MLR map data
p_precipitation_coeff_4	variable	From MLR map data
p_precipitation_coeff_5	variable	From MLR map data
p_max_temperature_elevation_lapse_rate	0.006	
p_min_temperature_elevation_lapse_rate	0.006	
p_bristow_and_campbells_a	0.766	
p_bristow_and_campbells_b	0.0327	
p_bristow_and_campbells_c	1.46	
p_origin_1	variable	From vegetation age map data
p_origin_2	variable	From vegetation age map data
p_origin_3	variable	From vegetation age map data
p_rain_interception_coeff	0.0008	
p_snow_interception_coeff	0.0008	
p_slope_leaf_water_potential_vs_rel_water_availability	-100000	
p_minimum_leaf_conductance	0.0002	
p_slope_leaf_cond_vs_cold_temp	0.0002	
p_slope_rel_leaf_cond_vs_warm_temp	0.0003	
p_canopy_species	variable	From vegetation type map data
p_canopy_radiation_extinction_coeff	0.37	
p_canopy_reflection_coefficient	0.19	
p_canopy_root_depth	4	
p_canopy_leaf_water_potential_at_stomatal_closure	-2300000	
p_canopy_leaf_water_potential_maximum	-500000	
p_maximum_canopy_leaf_conductance	0.005	
p_slope_canopy_relative_leaf_cond_vs_vpd	0.0003	
p_canopy_leaf_conductance_radiation_threshold	0	
p_canopy_reference_aerodynamic_resistance	15	
p_sat_canopy_transpiration_proportion	0.1	
p_canopy_leaf_conductance_radiation_parameter	100	
p_canopy_leaf_conductance_max_temperature	40	
p_canopy_leaf_conductance_optimal_temperature	25	
p_canopy_leaf_conductance_min_temperature	0	
p_min_temperature_causing_stomatal_closure	-8	
p_intercept_canopy_leaf_conductance_vs_lwp	-2000000	
p_shape_canopy_leaf_conductance_vs_lwp	400000	
p_canopy_leaf_conductance_vpd_factor	0.0007	
p_canopy_co2_for_max_leaf_conductance	350	
p_canopy_co2_causing_stomatal_closure	1050	
p_slope_soil_resistance_vs_vwc	-15000	
p_soil_resistance_vwc_threshold	0.2	
p_atmospheric_co2_concentration	350	
p_understorey_radiation_extinction_coeff	0.93	

p_understorey_species	-1	
p_understorey_reflection_coefficient	0.13	
p_understorey_root_depth	2	
p_understorey_leaf_water_potential_at_stomatal_closure	-2300000	
p_understorey_leaf_water_potential_maximum	-500000	
p_maximum_understorey_leaf_conductance	0.005	
p_slope_understorey_relative_leaf_cond_vs_vpd	-0.0003	
p_understorey_leaf_conductance_radiation_threshold	0	
p_understorey_canopy_aerodynamic_resistance	15	
p_sat_understorey_transpiration_proportion	0.5	
p_snow_reflection_coefficient	0.65	
p_min_snowpack_degree_days	-30	
p_snowmelt_coeff_temperature	0.001	
p_snowmelt_coeff_rad	0.12	
p_soil_reflection_coefficient	0.1	
p_soil_understorey_aerodynamic_resistance	15	
p_evaporation_depth	0.003	
p_soil_evaporation_tortuosity_factor	2	
p_water_reference_aerodynamic_resistance	75	
p_water_reflection_coefficient	0.05	
p_surface_saturated_hydraulic_conductivity	variable	Calibration parameter
p_minimum_saturated_hydraulic_conductivity	variable	Calibration parameter
p_saturated_hydraulic_conductivity_shape	variable	Calibration parameter
p_saturated_hydraulic_conductivity_depth	variable	Calibration parameter
p_ratio_hydraulic_to_surface_gradient	variable	Calibration parameter
p_saturated_volumetric_water_content	0.67	
p_residual_volumetric_water_content	0.2	
p_van_genuchten_n	1.8	
p_clay_fraction	0.15	
p_sand_fraction	0.35	
p_field_capacity_volumetric_water_content	0.45	
p_irrigation_threshold	0.85	