ESFM Project: Water Quality and Quantity for the Upper and Lower North East, Southern RFA Regions

A project undertaken as part of the NSW Comprehensive Regional Assessments

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ESFM PROJECT: WATER QUALITY AND QUANTITY FOR THE UPPER AND LOWER NORTH EAST, SOUTHERN RFA REGIONS

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In conjunction with CSIRO Land and Water

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EXECUTIVE SUMMARY

This working paper describes a project undertaken as part of the comprehensive regional assessments of forests in New South Wales. The comprehensive regional assessments (CRAs) provide the scientific basis on which the State and Commonwealth Governments will sign regional forest agreements (RFAs) for major forest areas of New South Wales. These agreements will determine the future of these forests, providing a balance between conservation and ecologically sustainable use of forest resources.

Project objectives

The objectives of this project were to review the available literature on the impacts of logging upon water quality and quantity, to collate relevant baseline resource information, and to develop and apply a methodology for modelling the impact of possible logging activities on water quality and quantity.

Methods

A literature review was undertaken to provide a thorough summary of our current understanding of the potential impacts of logging on water quantity and quality. A wide range of topographic, climatic and hydrologic data was collected and used to develop a methodology for assessing the impact of logging on water quality and quantity.

The modelling framework was developed specifically to suit the project objectives at a level of complexity commensurate with the available data. Results were obtained for seven trial catchments, though the developed methodology is applicable to all forested catchments in the NSW CRA regions. The models were used to assess the impact of logging activities for a site immediately downstream of each forest, as well as for a site further downstream that included a mixture of land uses.

Key results and products

Water Quantity

The overall form of the relationship adopted for modelling changes in water quantity is based on the response observed in the Melbourne water supply catchments (the “Kuczera” curve), though it is modified to incorporate an initial increase in yield for a short period immediately following forest disturbance and to be consistent with the limited evidence available from NSW forests. The initial increase in yield and return to pre-treatment levels between 4 and 10 years after disturbance is well established in the literature. Following the initial increase in yield, streamflows decrease to a minimum after about 30 years of age, followed by a gradual recovery back to old-growth conditions over the next 50 to 150 years (the exact timing and magnitude of this deficit and recovery are speculative).

In addition to the foregoing yield response relationship, the water quantity modelling is based upon two suppositions which are well established in the literature:

- the magnitude of the change in yield is linearly proportional to the area of forest logged, and
- the impacts are amplified by increases in mean annual rainfall – absolute impacts are diminished in drier areas.

The following conclusions can be made on the basis of the results of the water quantity modelling:

- the total expected *increase* in mean annual flow due to combined effects of both logging and tree growth ranges between 2% and 60%, and the corresponding total expected *decrease* is generally expected to be zero;
- the total expected *increase* in mean annual flow that is attributable solely to logging ranges between around 0% and 10%, and the corresponding total expected *decrease* in mean annual flow ranges between around 5% and 50%;
- the timing of these expected decreases and increases is dependent upon the current age of the forest and the adopted logging scenario; in general however, it is expected that the streamflow increases solely attributable to logging will peak within the next 10 years, and the maximum decreases will occur within the next 40 to 80 years;
- the impacts attributable solely to logging are not sensitive to the initial age profile adopted;
- the total expected impact on yield due to both logging and growth will vary depending on the initial age profile adopted.

Water Quality

Logging activities can impact on water quality in a number of ways, though the greatest impact (and hence focus of this study) is the increased level of suspended solids in streamflows. For the purposes of quantifying impacts, the main causes of disturbance that impact upon sediment production are logging activities within the general harvest and snig track area, and the maintenance and use of permanent access roads.

Based upon published and unpublished literature, probabilistic event-based *sediment generation rates* were derived for both the general harvest and snig track area, as well as the permanent access roads. Information on rainfall characteristics was then used to convert the event-based rates to site-specific annual loads. For the general harvest and snig track area a relationship was also established to define the decline in sediment production as a function of time since disturbance.

Spatial information on drainage lines, roads, soil erodibility, and forested catchment boundaries were imported into a GIS and analysed to provide site-specific relationships for the *proportion of the mobilised sediment that reaches the stream* from both the general harvest and snig track area, as well as the permanent access roads. The annual generation rates were combined with the site-specific delivery ratios to determine the annual sediment load reaching the drainage lines. The difference in sediment loads due to logging activities were then identified.

The following conclusions can be made on the basis of the results of the water quality modelling:

- the total estimated increase in sediment loads due to logging activities range between 10% and 70% of the current estimated loads;
- the majority of the increase in sediment load is generated by increased road traffic;
- the contribution from the general harvest and snig track area represents between 10% to 40% of the total increase in sediment load due to logging.

The adopted methodology provides a reasonable "best guess" that is unlikely to be much improved even with the expenditure of considerable further effort. While the absolute magnitude of the estimates are subject to considerable uncertainty, the models do codify our current best understanding of the different factors that influence water quantity and quality within the limitations of current data availability. The modelling approach thus provides a robust, credible, and objective basis for evaluating the impacts of logging, particularly if used to rank proposed activities in terms of relative disadvantages and merits.

1. INTRODUCTION

1.1 BACKGROUND

This working paper describes a project undertaken as part of the comprehensive regional assessments of forests in New South Wales. The comprehensive regional assessments (CRAs) provide the scientific basis on which the State and Commonwealth Governments will sign regional forest agreements (RFAs) for major forest areas of New South Wales. These agreements will determine the future of these forests, providing a balance between conservation and ecologically sustainable use of forest resources.

This project investigates impacts from forested land management on water quantity and quality in the Upper North East (UNE), Lower North East (LNE) and Southern regions. Water has been identified as an important issue for these regions and there appears to be issues with rural and town water supplies and potential impacts that forest activity may have on downstream water quantity and quality.

This project will provide the base information required to determine whether a full economic study is justified. If it is required then it would involve an assessment of the potential economic impacts of changes in water quantity and quality from forested catchments. This component will be done by the Economic and Social Technical Committee (E&S TC) and the project is described in Economic Assessment of Water Values circulated to the E&S TC on 1 July 1998.

1.2 OBJECTIVES

The objectives of this project are to:

- review the available literature on the impacts of logging and silviculture, roading and forestry plantations upon water quality and quantity.
- collate baseline resource information on water quality and quantity in the Upper/Lower North East and Southern NSW RFA regions.
- develop a methodology for modelling the impact of forest management on water quality and quantity.
- estimate the likely impacts on downstream catchments by applying the methodology to sample catchments.

1.3 SCOPE

The project is broken down into the following four tasks:

- *Literature Review:* This involved the review of the available literature on hydrologic aspects of different land use with the primary emphasis on forests. Attention was given to the impacts of logging and silviculture, roading and forestry plantations upon water yields, flows and quality.
- *Classification of downstream catchments:* Catchments downstream of State Forest areas were classified using the interim results of the *Stressed Rivers Assessment Process*. Each catchment was categorised in terms of hydrological stress, environmental stress, and an evaluation of conservation significance. A map of each CRA Region was prepared showing the different stress classifications of the catchments downstream of the forests.
- *Pilot Studies:* Considerable effort was spent on identifying suitable catchments that could be used to assess the impacts of logging activities using GIS tools and information on stream gauging. The overall criteria used to select the catchments was the availability of information to characterise the hydrology of the streams as they leave the State Forest area, and at some point downstream that includes mixed land use. For each catchment plausible logging scenarios were determined in consultation with the regional offices of State Forests NSW. The impact of the logging activity on downstream water quality and quantity was then determined using the developed models.
- *Reporting:* A large quantity of documentation and data was collated for the ESFM Group, and this report was prepared to detail the modelling methodology and the results of the pilot studies.

1.4 CONDUCT OF STUDY

The project was managed by the Department of Urban Affairs and Planning (DUAP) on behalf of the ESFM Group. As the study progressed the ESFM Group were provided with copies of the proposed approach to the study, then a brief description of the adopted methodology. Meetings were held with representatives of the ESFM Group on the 17th August and the 15th September 1998 to discuss the modelling approach. Numerous other discussions were held with stakeholders associated with the ESFM Group that had particular interests in the project outcomes.

Project management and modelling was undertaken by Sinclair Knight Merz, and the overall methodology was developed in conjunction with Dr Rob Vertessy, Dr Peter Hairsine and Dr Jacky Croke from the CSIRO Division of Land and Water. During the course of the project Dr Peter Cornish (State Forests NSW) also provided valuable comments and input to the adopted methodology. Pat O'Shaughnessy acted in an expert review role, particularly in regards to initial project scope and methodology. The literature review on water yield impacts was undertaken by Dr Rob Vertessy, and that for water quality impacts was undertaken by Dr Peter Hairsine and Dr Jacky Croke.

The collation of the necessary data and the determination of the most appropriate methodology required extensive consultation with a large number of people from the stakeholder agencies. Information was obtained from the head office and various regional offices of the Department of Land and Water Conservation, the Department of Urban Affairs and Planning, the Environment Protection Authority, the National Parks and Wildlife Service, and the head office and various regional offices of State Forests NSW. A list of the people contacted as part of the study is included in Appendix A.

The time constraints on the project in which to undertake the scope of work as outlined above was 6 weeks. The tight time constraints dictated that the modelling framework needed to be based on information that was published or readily available. The relationships adopted in the modelling were generally based upon those in the published literature and other unpublished results that were made available to the project team.

A large amount of data, and in particular Geographical Information System (GIS) data, were required for the project. Some of this information is being collated as part of the ongoing CRA process, but nearly all of the data required for the modelling was not available within the project timeframe and thus needed to be collated from the relevant agencies. Considerable project resources were spent seeking out the appropriate Agency contacts, determining data availability and then ordering the required data. A list of the information and references collated as part of the project (excluding those obtained for the literature review) is given in Appendix B.

2. YIELD REVIEW

2.1 INTRODUCTION

Water supply catchments of many Australian cities and rural townships are almost entirely covered by eucalypt forests. Management of these forests is thus an important aspect of water supply planning. Over the last three decades, there has been significant expansion of plantations (primarily pines), with over 1 million ha of land now under plantation cover across Australia. Both Commonwealth and State governments are committed to trebling our plantation area over the next two decades (DPIE, 1997). As most of the new plantations will be established in what are now grassland areas, significant streamflow changes may occur. This has important consequences for streamflow-dependent enterprises located downstream of plantations, particularly in situations where streamflows are already heavily allocated to users and the environment.

There is now broad agreement amongst researchers that forestry activities have the potential to alter catchment water balances and thus change the amount and timing of catchment streamflows. A large number of studies have been conducted throughout the world to ascertain the nature and extent of streamflow change likely to result from forestry activities of different kinds. This review examines the findings of those studies and seeks to develop generalisations about the effects of forest disturbance on streamflows. The focus in this review is mainly on water yield or the amount of streamflow, though attention is also given to streamflow seasonality and flow frequency, and the magnitude of peak flows.

Our knowledge of the effects of forest clearance on streamflows in Australia stems mainly from ten major sets of catchment treatment experiments, located in diverse geographic settings (Table 2.A). The earliest studies commenced in the late 1950’s, though most were only established in the 1970’s. Since the mid 1980’s, many of the catchment experiments have been abandoned, primarily due to cost cutting in the State resource agencies running them. Hence, unlike in the USA, Australia is not endowed with catchment treatment experiments which have been monitored over long time periods. The most complete and most reliable data on the impacts of forestry on streamflows come from the Maroondah, Karuah and Darling Ranges experiments. The brevity of Australian hydrologic records is a general weakness that precludes us from making definitive statements about the long term impacts of forestry on streamflows.

This review is framed around a series of questions commonly asked when consideration is given to the impacts of forestry on streamflows, namely:

- What are the fundamental hydrologic differences between forested and grassland areas that might lead to differences in streamflows?
- What effect does forest clearance have on streamflow?
- Do streamflows from native eucalypt forests and pine plantations differ?
- How does forest age affect streamflows?

- What affect do forestry activities have on streamflow regime?
- Are there factors which could alter the expected impacts of forest disturbance on streamflows?

A broad geographic focus is adopted in this review, though emphasis is placed on forest types and climatic conditions prevailing in south-eastern Australia. Particular attention is given to forest areas in NSW and the streamflow changes likely to arise from disturbance by logging, fire, and natural ageing.

This review concludes with a statement of current knowledge gaps and recommendations for future research in the field of forestry impacts on streamflow.

2.2 RELATED REVIEWS

There are several published reviews which summarise the impacts of forestry on streamflows. These vary greatly in emphasis, with some focussed on water yield, and others adopting a multiple water value approach. They cover a wide range of geographic areas, and whilst several ignore Australian conditions, they still provide useful insights into how catchment hydrology is affected by forestry activities. Key reviews referred to here to are listed in Table 2.A. Amongst these are several works based on Australian data.

2.3 THE WATER CYCLE - DEFINITION OF KEY TERMS

We begin this review with a brief description of the water cycle so that the studies we examine later can be properly interpreted. The key hydrologic processes referred to in this review are defined in Table 2.C.

Streamflow from catchments is generated from rainfall and discharge of groundwater, although the latter component is usually small. However, not all rainfall is converted into streamflow. Some rainfall is intercepted by vegetation or detained in ground depressions, and evaporates back into the atmosphere. Rain which infiltrates into the soil increases the soil water storage, though this is continually depleted by soil evaporation and the uptake of water by plants through the process of transpiration. In some cases, soil water percolates to deep groundwater systems and may not be intercepted by the gauging structure used to measure streamflow at the bottom of the catchment.

Summarising, the catchment water balance is described by the following equation:

$$Q = P - ET - R + D \pm \Delta S \tag{1}$$

where:

Q = streamflow
P = rainfall
ET = evapotranspiration
R = groundwater recharge
D = groundwater discharge
ΔS = change in soil moisture storage

TABLE 2.A LISTING OF THE MAIN AUSTRALIAN CATCHMENT TREATMENT EXPERIMENTS DESIGNED TO ASCERTAIN RELATIONSHIPS BETWEEN FORESTRY ACTIVITIES AND STREAMFLOWS.

Study	Location	Study managers	Focus	Key references
Maroondah	Near Healesville, VIC Central Highlands	Melbourne Water	Effect of mountain ash forest age and harvesting methods on water yield and quality	Langford 1976; Langford and O'Shaughnessy 1977; Langford and O'Shaughnessy 1980; Moran and O'Shaughnessy 1984; Kuczera 1987; Haydon 1993; Jayasuriya *et al.* 1993; Haydon *et al.* 1996; Watson *et al.* 1998
Karuah	Near Dungog, NSW lower north east region	NSW State Forests	Effect of forest harvesting methods on water yield and quality	Cornish (1993); Cornish and Vertessy (1998)
Yambulla	Near Eden, NSW south east region	NSW State Forests	Effect of forest harvesting methods and fire on water yield and quality	Mackay and Cornish 1982; Moore et al 1986; Mackay and Robinson 1987
Redhill	Near Tumut, NSW southern uplands	NSW State Forests	Water yield and quality impact of pasture conversion to pine plantation	Nothing yet published
Lidsdale	North-west of Sydney, NSW	University of New South Wales and NSW State Forests	Water yield impact of eucalypt forest conversion to pine plantation	Smith *et al.* 1974; Pilgrim *et al.* 1982
Parwan	North-west of Melbourne, VIC	NRE, Victoria	Water yield impact of eucalypt forest conversion to pasture	Nandakumar and Mein 1993
Stewarts Creek	Near Ballarat, central VIC	NRE, Victoria	Water yield impact of eucalypt forest conversion to pine plantation and pasture	Nandakumar and Mein 1993
Croppers Creek	Near Myrtleford, VIC north-eastern highlands	NRE, Victoria	Water yield and quality impact of eucalypt forest conversion to pine plantation	Bren and Papworth 1991
Babinda	South of Cairns, QLD	QDPI and James Cook University	Impacts of rainforest clearance on runoff generation	Bonell and Gilmour 1978; Cassells *et al.* 1985
Darling Ranges	South of Perth, south-western WA	CALM, WA, Water Authority, WA and Alcoa	Impacts of clearing jarrah forest on water yields and salinity	Ruprecht and Schofield 1989; Ruprecht and Schofield 1991; Ruprecht and Stoneman 1993; Stoneman 1993

TABLE 2.B LIST OF REVIEWS FOCUSSING ON THE HYDROLOGIC IMPACTS OF FOREST DISTURBANCE

Published Review	**Details**
Overseas studies	
Bosch and Hewlett 1982	One of the most quoted review papers on water yield, focussing on 94 worldwide studies
Bruijnzeel 1990	The most comprehensive account of water balance and water yield in moist tropical forests
Schofield 1996	A general review of the impacts of forestry on water values, including reference to Australian studies; largely based on other reviews
Stednick 1996	Reviews 95 studies from the United States in a similar manner to Bosch and Hewlett (1982)
Dye 1996	Focuses on water yield changes arising from afforestation of grasslands in South Africa with eucalypts and pines
Australian studies	
Cornish 1989	Summarises Australian, New Zealand and South African research on water yield from Pine plantations, making reference to grassland and eucalypt forests also
Doeg and Kohen 1990	Examines 36 Australian studies in a case study format, considering a range of water values
Dargavel *et al.* 1995	Summarises the hydrologic impacts of logging, focussing on south-eastern Australia; also addresses related economic and policy issues

TABLE 2.C DEFINITION OF KEY HYDROLOGIC TERMS REFERRED TO IN THIS REVIEW.

Process	**Definition**
Rainfall	Precipitated water arriving at the plant canopy
Interception	Detention (and subsequent evaporation) of water stored on plant surfaces
Surface detention	Detention (and subsequent evaporation) of water stored in surface depressions
Stemflow	Movement of water down the stems of plants, to the soil surface
Transpiration	Evaporation of water via the stomata in leaves of plants
Soil evaporation	Evaporation of water from the soil
Evapotranspiration	The sum of interception, surface detention, transpiration and soil evaporation
Infiltration	Movement of water into the soil profile
Percolation	Movement of water through the soil profile
Soil moisture storage	Storage of water in the soil profile
Subsurface flow	Movement of water through the soil
Overland flow	Movement of water over the soil surface
Groundwater recharge	Drainage from the soil profile to a groundwater system
Groundwater discharge	Flux of water from a groundwater system into the soil profile
Streamflow	Sum of overland and subsurface flow, and groundwater discharge, measured in a stream channel

In other words, streamflow over any given time period is the residue of rainfall once evapotranspiration, groundwater exchange and changes in soil storage have been accounted for. By changing land use, several of these water balance terms can be modified and thus influence streamflow.

2.4 FUNDAMENTAL HYDROLOGIC DIFFERENCES BETWEEN FORESTED AND GRASSLAND AREAS THAT MIGHT LEAD TO DIFFERENCES IN STREAMFLOWS

Streamflows from forests are generally lower than from grasslands because forests have higher evapotranspiration (ET) rates than grasslands. This is so because forests have:

- higher and more persistent leaf area than grasses, leading to greater rainfall interception and greater transpiration;
- greater aerodynamic roughness than grasses, leading to greater rainfall interception and greater transpiration; higher roughness also enhances the likelihood that advected warm, dry air can supplement the radiant energy input (see Calder, 1997);
- deeper rooting than grasses, enabling better access to soil water, leading to greater transpiration;
- a greater ability to extract moisture from the soil under dry conditions, leading to greater transpiration;
- lower albedo than grasses, meaning more absorption of radiant energy, leading to greater transpiration.

Table 2.D lists a variety of ET estimates for grassland and forests in south-eastern Australia, determined from catchment treatment experiments. Annual ET from grassland is usually less than 700 mm, whereas annual ET from forests can approach 1300 mm. Streamflow from forests is uncommon in areas with annual rainfall less than 800 mm, unless rainfall is highly concentrated in a particular season. Table 2.D shows that there is considerable variation in mean annual ET in forests. This is largely a consequence of varying rainfall amounts, though there are species, productivity and age effects which are also quite important. Such effects are examined in later sections of this review.

Holmes and Sinclair (1986) examined rainfall/runoff relationships for 19 large catchments across Victoria, with mean annual rainfalls ranging between 500 and 2500 mm, and varying mixtures of grass and eucalypt forest cover. They demonstrated that there were clear differences between ET rates for grassland and eucalypt forest catchments and conceptualised this with a pair of curves that emphasised the differences along a rainfall gradient (Figure 2.A). According to these curves, a fully forested eucalypt catchment would evapotranspire 40, 90, 215, 240 and 250 mm more per year than a fully grassed catchment with mean annual rainfalls of 600, 800, 1300, 1500 and 1800 mm, respectively. An analysis by Cornish (1989) on different hydrologic data yielded very similar figures to these [see his Table 4, p.17].

TABLE 2.D MEAN ANNUAL RAINFALL AND EVAPOTRANSPIRATION (ET) FOR CATCHMENTS WITH VARIOUS VEGETATION COVERS IN SOUTH-EASTERN AUSTRALIA.

Location	Details	Vegetation	Annual rainfall (mm)	Annual ET (mm)	Reference
Parwan (1-6), VIC	over 6 years of data from each of six catchments - NRE, VIC	native and improved pastures, some grazed	538	491	Nandakumar and Mein 1993
Lidsdale 1, NSW	3 years of data from one catchment - UNSW	grass, weeds, pines seedlings with little LAI	688	567	Pilgrim *et al.* 1982
Mt. Gambier, SA	6 years of data from one catchment - CSIRO Soils	grass	~670	580	Holmes and Sinclair 1986
Kylies Run, Tumut, NSW	7 years of data from one catchment - NSW State Forests	improved pasture, grazed	944	691	NSW State Forests (unpublished data)
Pomaderris, Eden, NSW	7 years of data from one catchment - NSW State Forests	mature, dry eucalypt forest	973	775	NSW State Forests (unpublished data)
Peppermint, Eden, NSW	3 years of data from one catchment - NSW State Forests	mature, dry eucalypt forest	1103	826	NSW State Forests (unpublished data)
Sassafras, Karuah , NSW	7 years of data from one catchment - NSW State Forests	mature, moist eucalypt forest, rainforest	1434	1128	Cornish 1993
Crabapple, Karuah , NSW	7 years of data from one catchment - NSW State Forests	mature, moist eucalypt forest, rainforest	1639	1190	Cornish 1993
Picaninny, Maroondah, VIC	3 years of data from one catchment - Melbourne Water	old growth mountain ash forest, rainforest	1180	848	Vertessy *et al.* 1996
Myrtle 1, Maroondah, VIC	11 years of data from one catchment - Melbourne Water	old growth mountain ash forest, rainforest	1598	882	Vertessy *et al.* 1993
Picaninny, Maroondah, VIC	10 years of data from one catchment - Melbourne Water	regrowth mountain ash forest (age 15-25), rainforest	1245	1061	Melbourne Water (Unpublished data)
Ettercon 3, Maroondah, VIC	11 years of data from one catchment - Melbourne Water	regrowth mountain ash forest (age 33-44), rainforest	1631	1250	Melbourne Water (Unpublished data)
Reefton (1-6), Vic	10 years of data from six catchments - Melbourne Water	mature mountain ash and mixed eucalypt forest	1298	1022	Nandakumar and Mein, 1993

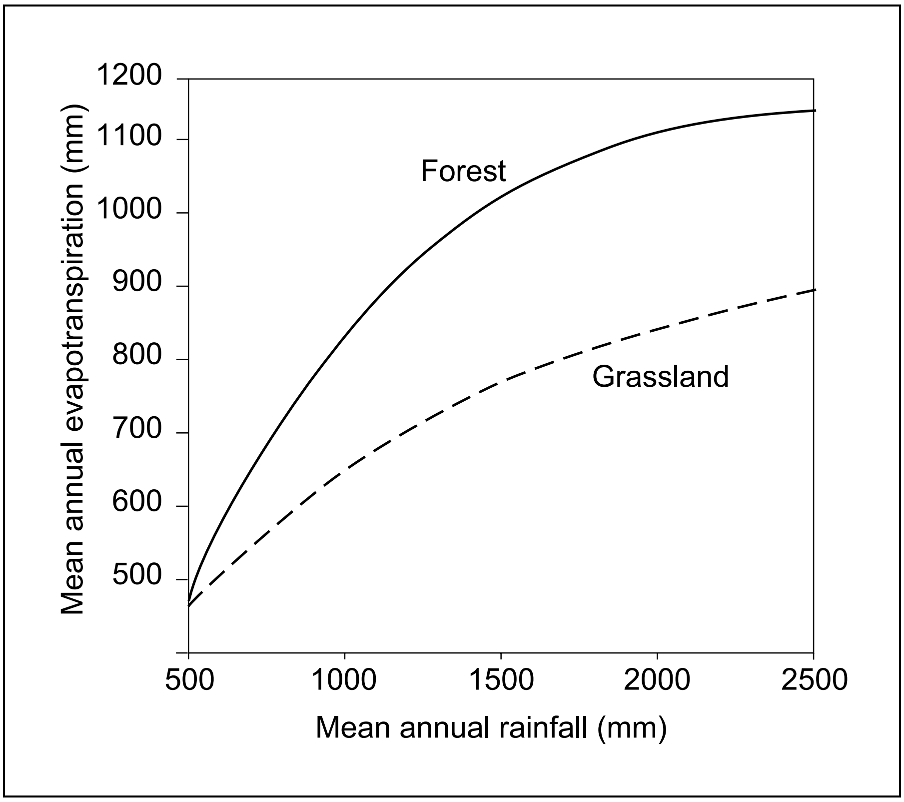

FIGURE 2.A MEAN ANNUAL EVAPOTRANSPIRATION FROM PASTURES AND FOREST AS A FUNCTION OF MEAN ANNUAL RAINFALL (ADAPTED FROM HOMES AND SINCLAIR, 1986).

The Holmes and Sinclair (1986) relationship (HSR) is a useful generalisation to obtain a quick estimate of ET (and hence streamflow) for catchments at different isohyets. However, the relationship is not always applicable. For instance, Moran and O'Shaughnessy (1984) reported mean annual ET estimates for 17 catchments in the Maroondah basin, all of which are fully forested with the same eucalypt species (mountain ash). Their ET estimates vary between 740 and 1330 mm per year for catchments with mean annual rainfalls of between 1160 and 1880 mm (Figure 2.B). Figure 2.B shows that mean annual ET rates for catchments with similar rainfall vary by as much as 300 mm, indicating that the HSR is only a rough guide to likely ET rate in catchments. Moran and O'Shaughnessy (1984) attribute these ET differences to variations in forest age and stocking rate. These effects will be discussed later in this review.

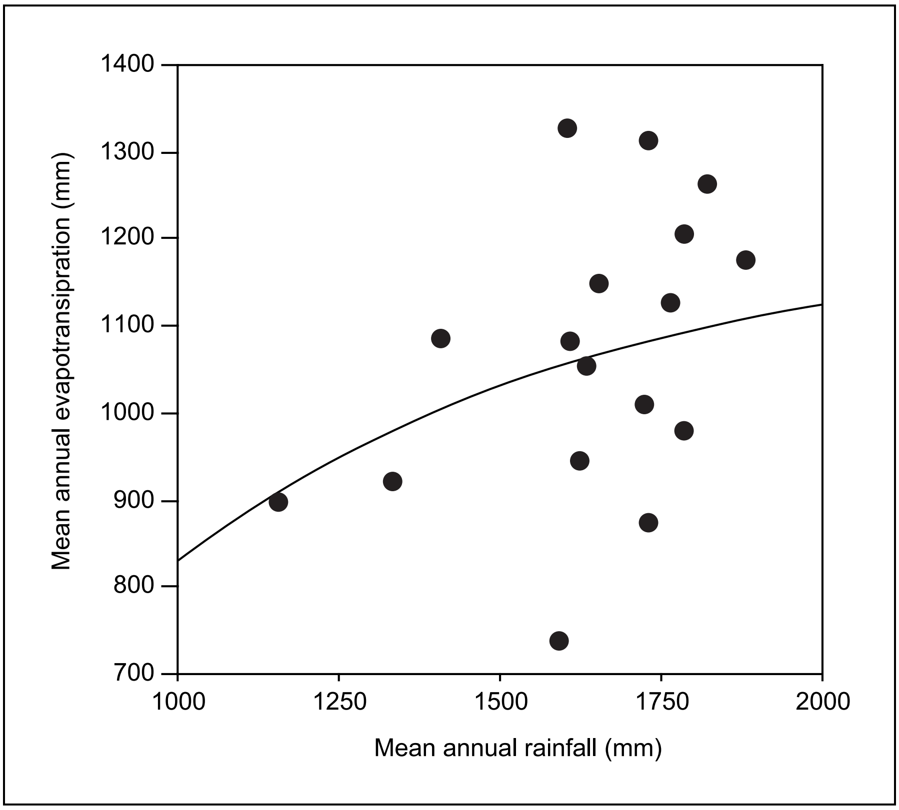

FIGURE 2.B RELATIONSHIP BETWEEN MEAN ANNUAL EVAPOTRANSPIRATION AND RAINFALL OVER A THREE YEAR PERIOD FOR 17 FULLY FORESTED MOUNTAIN ASH FOREST CATCHMENTS IN THE MAROONDAH BASIN, VICTORIA. DATA FROM MORAN AND O'SHAUGHNESSY 1984). SOLID LINE DENOTES THE HOLMES AND SINCLAIR (1986) RELATIONSHIP FOR EUCALYPT FOREST.

2.5 EFFECT OF FOREST CLEARANCE ON STREAMFLOWS

Most catchment water balance studies conducted to date have been framed around the question of what is the effect of forest clearance on streamflows. Almost all of the studies have shown that streamflow increases as forest cover decreases, and vice versa. They also show that the magnitude of increase varies as a function of the type of forest treated and the mean annual rainfall of the site.

Most of the data reported below is based on catchment treatment experiments where the forest cover is cleared or partially cleared. In some cases, the forest is permitted to regenerate, so only the first few years of data following treatment are used in building such relationships. This is problematic for three reasons. Firstly, it takes time for a catchment to adjust it's runoff behaviour. Immediately after clearance, some rainfall is used to replenish the soil water deficit left by the higher ET forest that has been removed. This has the effect of tending to underestimate the effect of forest clearance. Secondly, it is possible that soil disturbance from logging activities can temporarily increase overland flow and change the pattern of streamflow. This has the effect of tending to overestimate the effect of forest clearance, thus off-setting the first effect. Thirdly, because of the short time span used to build the relationship, it is possible that rainfall variability will complicate the catchment response. Depending on the rainfall pattern, this could result in either an underestimate or overestimate of the effects of forest clearance.

On the other hand, much of the data from South Africa and New Zealand is based on afforestation experiments. Results from South African studies tend to be based on long data records, often exceeding 30 years in length.

2.5.1 Northern hemisphere studies

Hibbert (1967) summarised the results of 39 catchment experiments carried out in the USA, mainly on deciduous hardwood and conifer forests. He concluded that:

- reduction of forest cover increased water yield;
- afforestation decreased water yield; and,
- the response to treatment was highly variable and unpredictable.

Bosch and Hewlett (1982) added another 55 catchment studies to the Hibbert (1967) data set, including results from Japan, Australia, New Zealand and South Africa. Figure 2.C shows their conclusion that water yield increases proportionately with the percent area of forest cleared, but indicating a fair degree of scatter in the relationship. Bosch and Hewlett (1982) related much of this scatter to species differences. Figure 2.D shows the trend lines they fitted to the data in Figure 2.C for three different woody species (conifers, deciduous forest and scrub). This indicated that the rate of yield increase is greatest for conifers, and least for scrub. They hypothesised that vegetation growth rate was thus a key control on the likely response of a catchment to disturbance. Figure 2.D shows that each 10% reduction in forest cover results in an annual yield increase of 40 mm for conifers, 25 mm for deciduous hardwoods, and 10 mm for scrub. Bosch and Hewlett (1982) also concluded that water yield changes could not be detected unless more than 20% of the catchment area was cleared.

More recently, Stednick (1996) reviewed 95 paired catchment studies from various geographic regions in the USA. His estimated yield increases accompanying forest clearance (shown in Table 2.E) were similar to those obtained by Bosch and Hewlett (1982), though his data is very scattered. Stednick (1996) fitted a linear relationship through his entire data set to determine the general rate of increase in water yield as a function of percent area of forest cleared. His line of best fit indicated an increase of about 25 mm in annual yield for each 10% of forest area cleared, though the r^2 value for this relationship was only 0.17 and the standard error was 149 mm. Breaking the data down by region, he found that the increase rate varied between 7 and 61 mm per 10% of forest area cleared. Based on his ‘all areas’ relationship, Stednick (1996) concluded that about 20% of the forest area needed to be cleared before any water yield change could be detected, supporting the earlier finding of Bosch and Hewlett (1982). However, after breaking the data down by region, he determined that the threshold area varied between 15 and 50%.

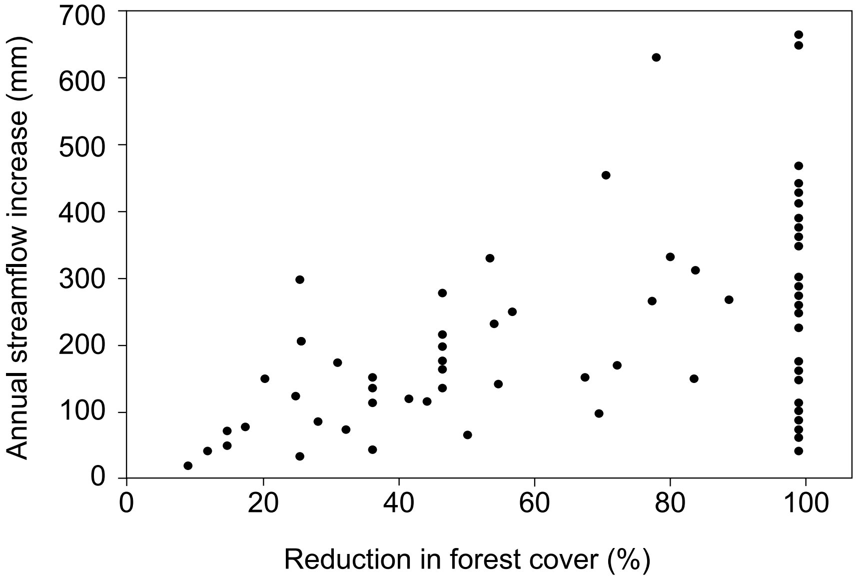

FIGURE 2.C RELATIONSHIP BETWEEN REDUCTION IN FOREST COVER AND INCREASE IN WATER YIELD (ADAPTED FROM BOSCH AND HEWLETT, 1982).

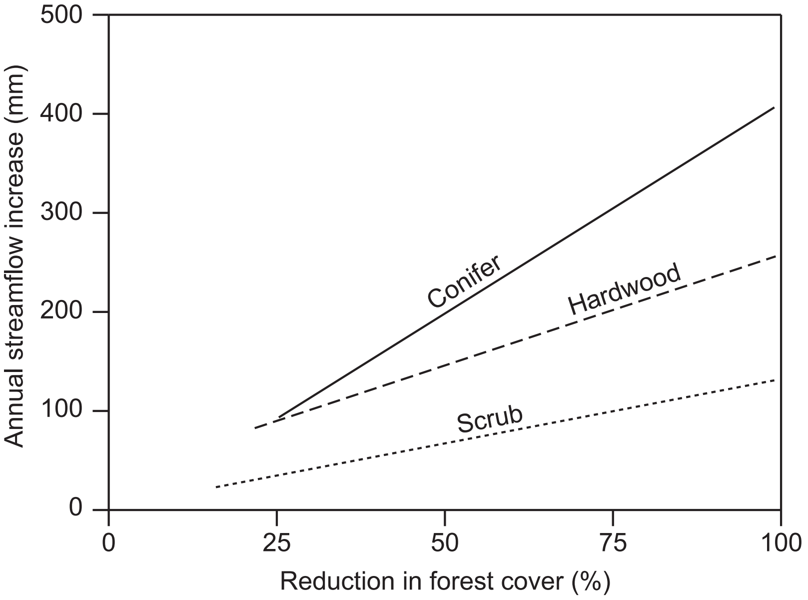

FIGURE 2.D GENERAL TREND LINES SHOWING THE RELATIONSHIP BETWEEN CLEARED AREA AND YIELD INCREASE FOR THREE DIFFERENT TYPES OF WOODY VEGETATION (ADAPTED FROM BOSCH AND HEWLETT, 1982 AND CORNISH, 1989).

TABLE 2.E ESTIMATED ANNUAL YIELD INCREASE PER 10% OF CATCHMENT AREA CLEARED OF FOREST (AYI/10%) FOR VARIOUS GEOGRAPHIC REGIONS IN THE USA (AFTER STEDNICK, 1996).

Region	#	AYI/10% (mm)	r^2	SE (mm)	Threshold (%)
All areas	95	25	0.17	149	20
Appalachia	29	28	0.65	75	20
East Coast	7	19	0.02	97	45
Rocky Mountains	35	9	0.01	66	15
Pacific Coast	12	44	0.65	118	25
Central Plains	7	61	0.31	197	50

# denotes the number of studies included in each relationship, SE denotes the standard error, and r^2 denotes the goodness of fit. The 'threshold' is the percent forest area needed to be cleared before a water yield change can be detected

Stednick (1996) fitted a similar relationship to the Bosch and Hewlett (1982) data set shown in Figure 2.C, pooled with some English data reported by Calder (1993). That relationship predicted a general increase in annual yield of about 33 mm for every 10% of forest area cleared, and was characterised by an r2 value of 0.50 and a standard error of 89 mm.

Summarising results from a large number of studies in the north-east USA, Hornbeck *et al.* (1993) determined that the first year increase in streamflows following clearance varied between 12 and 35 mm per 10% of forest area cleared. Hornbeck *et al.* (1993) stressed the importance of felling configuration and clearance method as a determinant of catchment response. They noted that streamflow increases were greatest in catchments where the forest was cleared from the valley bottom runoff-producing areas.

Bosch and Hewlett (1982) assessed the influence of mean annual rainfall on water yield increases caused by forest clearance. They scaled the data shown in Figure 2.C to represent yield increases that would occur if the entire forest area was cleared in the catchments examined. Figure 2.E shows that water yield gains caused by total removal of conifers and scrub generally increase as a function of mean annual rainfall. Also shown in Figure 2.E are the yield increases predicted by the Holmes and Sinclair (1986) relationship (HSR) for eucalypt forest conversion to grassland. The yield increases predicted by HSR are similar to the scrub values determined for low rainfall areas (400-700 mm), and are on the low side of the conifer values determined for intermediate rainfall areas (700-1400 mm). For the higher rainfall areas (above 1400 mm), the HSR estimates of yield increase are much lower than predicted by Bosch and Hewlett (1982) for conifers. For instance, according to Figure 2.E, conifer clearance in an area with mean annual rainfall of 1800 mm results in an annual water yield increase of between 400 and 450 mm. HSR estimates that eucalypt forest conversion to grassland in this rainfall regime causes an annual yield increase of 250 mm, while Cornish (1989) predicts an increase of 285 mm (see his Table 4, p. 17).

2.5.2 Tropical and subtropical forest studies

Bruijnzeel (1990) reviewed some 20 paired catchment studies based in various humid tropical and subtropical countries. He argued that the direction and magnitude of water yield changes accompanying forest clearance in these countries were similar to those reported by Hibbert (1967), Bosch and Hewlett (1982) and Stednick (1996) for temperate forests of the northern hemisphere. Bruijnzeel (1990) noted that light selective harvesting usually had little effect on streamflow, and that the effect increased with the amount of timber removed. He also showed that afforestation of grasslands or croplands with pine or eucalypts caused water yield to decrease and remain at lower levels.

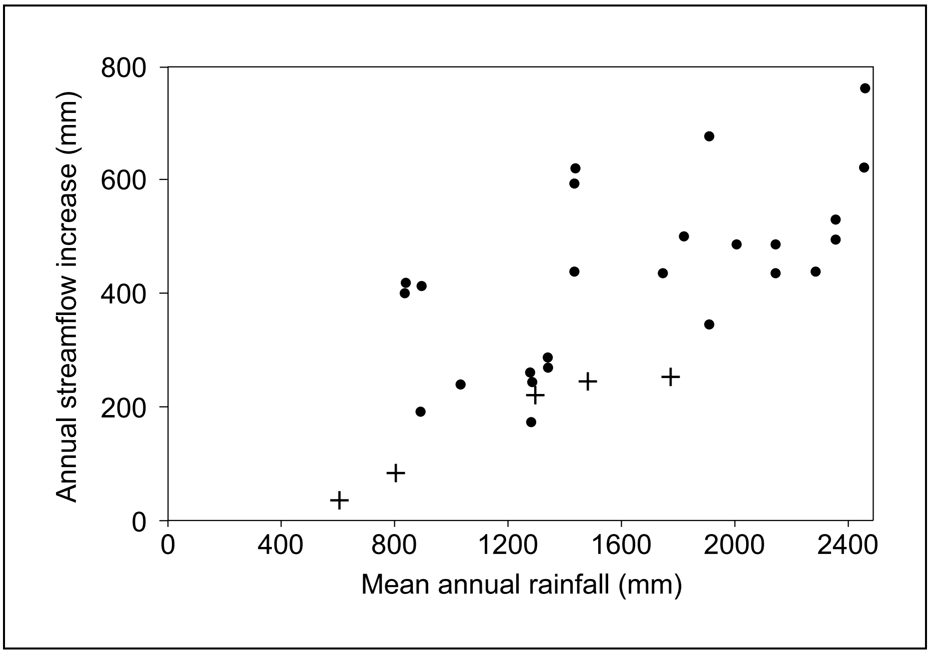

FIGURE 2.E EFFECT OF MEAN ANNUAL RAINFALL ON WATER YIELD INCREASES CAUSED BY TOTAL CLEARANCE OF CONIFER AND SCRUB VEGETATION FROM CATCHMENTS, ADAPTED FROM BOSCH AND HEWLETT, 1982. CROSSES DENOTE THE EXPECTED WATER YIELD GAINS FROM CONVERSION OF EUCALYPT FOREST TO GRASSLAND, BASED ON THE HOLMES AND SINCLAIR (1986) RELATIONSHIP.

2.5.3 New Zealand studies

Most New Zealand studies focus on the streamflow impacts of converting indigenous, mixed evergreen forest and native tussock grassland to pine plantations. These studies show that pine afforestation causes significant reductions in streamflow, particularly when displacing native tussock grasslands.

Dons (1986) reported a mean annual streamflow decline of 83 mm in a large basin vegetated with scrub that had 28% of its area afforested with pines. This equates to a streamflow decline of 30 mm per 10% of catchment afforested. Faye and Jackson (1997) cite streamflow increases ranging between 22 and 67 mm per 10% of forest area cleared, for the first year after clearance of indigenous forest at Maimai and Big Bush in the South Island of New Zealand (Table 2.F). For the seven catchments they examined, the average streamflow increase was 44 mm per 10% of forest cleared.

TABLE 2.F ANNUAL INCREASES IN STREAMFLOW IN THE FIRST YEAR AFTER CLEARANCE OF INDIGENOUS FOREST AT MAIMAI AND BIG BUSH, NEW ZEALAND (AFTER FAHEY AND JACKSON 1997).

Catchment	Mean annual rainfall (mm)	Streamflow increase per 10% of forest cleared (mm)
Maimai M9	1930	67
Maimai M7	1930	65
Maimai M5	2625	55
Big Bush DC1	1305	37
Big Bush DC4	1305	37
Maimai M8	2827	27
Maimai M13	2625	22

2.5.4 South African studies

Wood products from plantations contribute about 2% of the GDP in South Africa (Versfeld 1993). According to Dye (1996), the plantations are primarily based on pine (51%) and eucalypt (29%) species, and are confined to a relatively small area of the country which has an annual rainfall of more than 700 mm. These plantations have mostly replaced native scrub and grasslands. There is considerable evidence showing that the plantations have significantly higher ET rates than the original indigenous vegetation, and that streamflows have declined markedly as a result of afforestation. It is worth noting that most of the South African data is based on afforestation studies, rather than forest harvesting experiments. In general, the data sets are of high quality and are long term in nature, with many studies having post-treatment records exceeding 30 years in length.

Bosch (1979) reported that the afforestation of 74% of a catchment under native grassland with *P. Patula* reduced annual streamflow by about 260 mm over a period of 27 years after planting, equivalent to a decline of 35 mm per 10% of catchment afforested. Van Wyk (1987) reported mean annual streamflow declines of 313, 197 and 171 mm for three grassland catchments afforested with pines in the South Western Cape Province of South Africa. These catchments had plantations established on 98, 57 and 36% of their areas, respectively. Hence, the rates of streamflow decline equate to 32, 35 and 47 mm per 10% of catchment afforested, respectively. The 47 mm value seems to be unusually high when compared to other South African data, suggesting that it may be an artefact of the small area afforested (36%) in that particular experiment.

Dye (1996) summarised the results of seven catchment studies carried out by Bosch and von Gadow (1990), Smith and Scott (1992) and Versfeld (1993). He graphed ET changes resulting from afforestation, demonstrating that the speed and magnitude of response varied depending on the type of vegetation change and the mean annual rainfall of the catchment (Figure 2.F). The annual ET in six of the catchments under the indigenous scrub or grassland vegetation ranged between 700 and 950 mm, and increased to between 1050 and 1330 mm after afforestation. The rate of increase was higher for eucalypts than pine, reflecting the relatively rapid initial growth and canopy closure of eucalypt stands in South Africa. Dye (1996) concluded that where the demand for runoff is high, plantations of pines are preferable to eucalypts. As will be shown later in this review, this conclusion contradicts Australian findings on comparative rates of ET and streamflow for pine plantations and eucalypt forests.

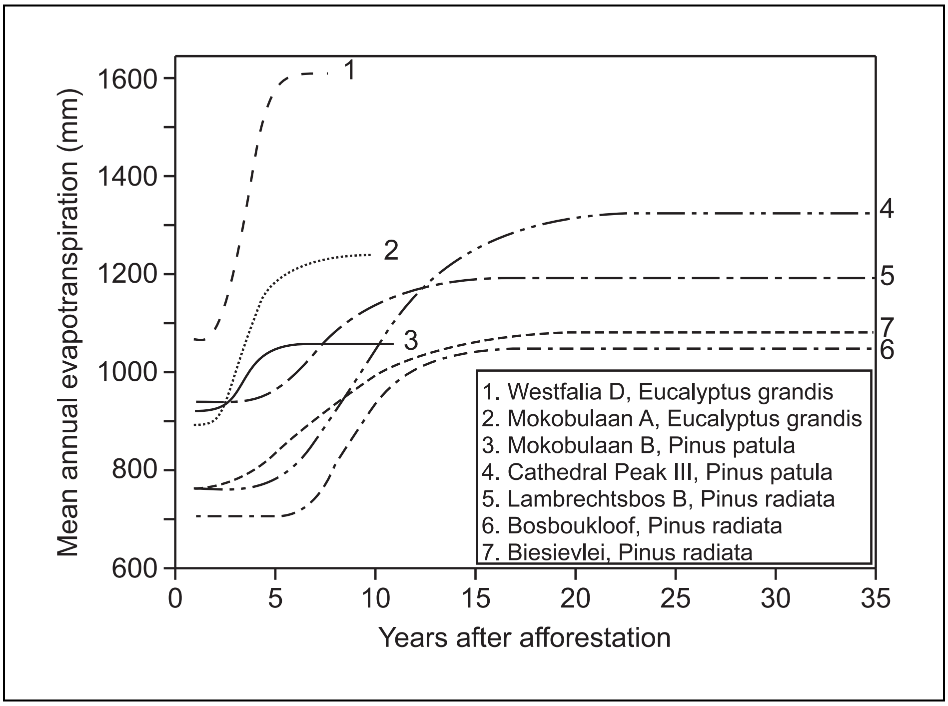

FIGURE 2.F EVAPOTRANSPIRATION TRENDS IN AFFORESTED SOUTH AFRICAN CATCHMENTS (AFTER DYE 1996).

2.5.5 Australian studies

Pooling data from the Maroondah, Stewarts Creek and Reefton catchments in Victoria, Nandakumar and Mein (1993) quantified the impact of eucalypt forest clearance on streamflows (Figure 2.G). They determined that streamflow increased by 33 mm for each 10% of forest area cleared. The linear regression underpinning this relationship had an r^2 value of 0.88 and a standard error of 43 mm, meaning that it is a lot stronger (statistically speaking) than the relationships published by Bosch and Hewlett (1982) and Stednick (1996). The average rainfall of the sites they examined was about 1400 mm. The Holmes and Sinclair (1986) relationship (Figure 2.A) suggests that conversion of forest to grassland at this rainfall isohyet should yield an additional 240 mm of streamflow, whereas Figure 2.G suggests a value of 330 mm. This difference is partly explained by the fact that the Holmes and Sinclair (1986) value is based on mean annual streamflow increase, whereas the Nandakumar and Mein (1993) value is based on the maximum streamflow increase.

The Nandakumar and Mein (1993) estimate of maximum streamflow increase (33 mm per 10% of forest area cleared) lies between the conifer and deciduous hardwood values reported by Bosch and Hewlett (1982), these being 40 and 25 mm, respectively. This value is very similar to mean values reported by Bosch (1979), Van Wyk (1987) and Dye (1996) for South African scrub and grassland catchments afforested with pines and eucalypts (32-35 mm per 10% area afforested). However, it lies towards the low end of the range determined for cleared indigenous forests in New Zealand (Table 2.F).

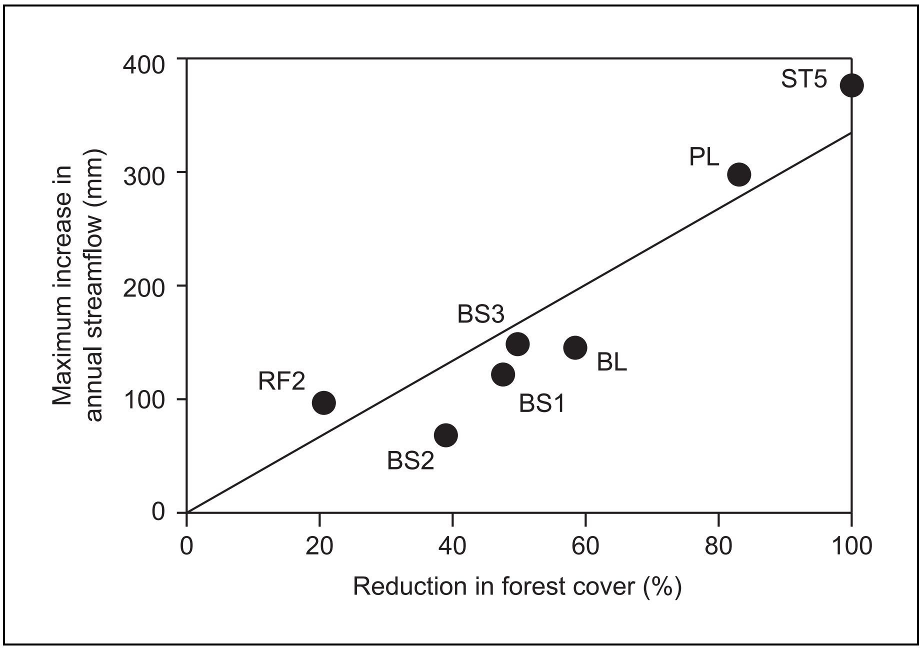

FIGURE 2.G RELATIONSHIP BETWEEN MAXIMUM ANNUAL STREAMFLOW INCREASE AND PERCENT AREA OF FOREST CLEARED FOR SEVEN CATCHMENTS IN VICTORIA (AFTER NANDAKUMAR AND MEIN 1993).

Cornish and Vertessy (1998) reported maximum annual streamflow increases of 40 to 50 mm per 10% of forest area cleared in four of the six treated Karuah catchments (Table 2.G). A fifth catchment (Kokata) yielded additional streamflow of 70 mm per 10% forest area cleared, though this was shown to have been heavily compacted, leading to greatly enhanced surface runoff. A sixth catchment (Barrata) did not experience a streamflow increase, though this was only logged over a relatively small area (25%) which is close to the ‘detection limit’ in studies of this kind. The logging-induced streamflow increases reported for Karuah are slightly higher than reported for other Australian studies.

TABLE 2.G MAXIMUM ANNUAL INCREASES IN STREAMFLOW AFTER CLEARANCE OF EUCALYPT FOREST AT KARUAH, NSW (BASED ON DATA FROM CORNISH AND VERTESSY 1998).

Catchment	Mean annual rainfall (mm)	Streamflow increase per 10% of forest cleared (mm)
Kokata	1599	70
Bollygum	1532	56
Coachwood	1472	43
Corkwood	1694	43
Jackwood	1391	37
Barrata	1657	0

Cornish (1991) reported a peak annual streamflow increase of 35 mm per 10% of logged area for the Eden 2 catchment, part of the Yambulla group of catchments. However, he also showed that the Eden 3 catchment experienced an annual streamflow rise of only 20 mm per 10% of forest area cleared. Cornish (1991) attributed the higher rate of increase in Eden 2 to the fact that this catchment was burnt after logging, hence reducing surface cover and possibly causing an hydrophobic effect in the soils that would increase surface runoff.

Mackay and Robinson (1987) do not report annual streamflow amounts for the Yambulla catchments but argue that streamflows increased by factors of 2.1, 6.8, 4.9 and 5.5 in the four treated catchments in the three years following forest clearance and/or fire (their Table 9, p. 378). It should be noted that these values represent absolute changes, and are not scaled to percent area of forest treated.

Roberts (per. comm.) analysed streamflow changes ensuing from logging and fire in the Eden 5 and 6 catchments. She determined maximum annual streamflow increases of 38 and 16 mm per 10% of forest area treated in Eden 5 and 6, respectively.

2.5.6 Transience and persistence of streamflow increases after clearance

The results presented in the preceding sections focussed mainly on (a) conversion of forest to grassland or vice versa, or (b) the few years immediately after forest clearance. In the former case, average changes in annual streamflow were reported, whereas in the latter case, the maximum reported increase in yield was usually reported.

In a forest which is cleared *but permitted to regenerate*, streamflow increases are both transient and temporary. Streamflow increases normally reach a peak in the second or third year after clearance, then decline to pre-treatment levels over a period of between 5 and 25 years, depending on rainfall, soil factors and forest growth rates. In some cases, streamflows then *decline below pre-treatment levels*. Such cases will be examined in later sections of this review.

Summarising results from 11 long-term catchments studies in the north-east USA, Hornbeck *et al.* (1993) noted that post-logging streamflow increases rarely persisted more than 10 years. However, he also noted examples where the streamflow increases had been purposefully maintained by the intermediate cuttings and the periodic application of herbicides to control regrowth. In these cases, streamflow increases over pre-treatment levels were maintained for over 20 years.

Nandakumar and Mein (1993) studied the transience of streamflow changes in the few years following forest clearance and regeneration in six eucalypt forest catchments in Victoria. They determined that peak streamflow increases were attained 2 or 3 years after clearance and that recovery to pre-treatment streamflow levels was reached anywhere between 5 and 25 years later (Table 2.H). As has been noted in north American studies (Swank *et al.*, 1988; Hornbeck *et al.* 1993), Nandakumar and Mein (1993) found that streamflows declined at a logarithmic rate once the peak increase had been attained. They provide an equation with fitted parameters to predict streamflow recovery rates for the six catchments they studied.

For the Karuah catchments, Cornish and Vertessy (1998) showed that streamflow increases peaked two or three years after clearance and returned to pre-treatment levels within a period of between four and eight years. They noted that the rate of decline in streamflow after the peak increase was proportional to the stocking rate of the regenerating forest. This finding is consistent with world experience which suggests that streamflow changes are most shortlived in forests of high productivity; the quicker the new forest canopy can form and close over, the quicker streamflows will return to pre-treatment levels.

TABLE 2.H MAGNITUDES AND TIME SCALES OF STREAMFLOW INCREASES FOLLOWING FOREST CLEARANCE IN SIX VICTORIAN CATCHMENTS (AFTER NANDAKUMAR AND MEIN 1993).

Catchment	Time to reach peak streamflow (years)	Maximum annual streamflow increase (mm)	Time for streamflow to return to pre-treatment level (years)
Stewarts Creek 5	3	296	20
Black Spur 1	2	145	8
Black Spur 2	2	64	5
Black Spur 3	2	137	25
Picaninny	2	388	7
Blue Jacket	2	190	8

Note: The catchments had variable areas of forest cleared. The time to recovery is a predicted value, based on a logarithmic equation.

In her analysis of streamflow changes at Eden 5 and 6, Roberts (pers. comm.) found that the maximum increase in streamflow in both catchments was only attained six years after treatment. This is much later than observed for most catchments in the international literature, and may be due to the highly variable rainfall pattern in the immediate post-treatment period. She also noted that recovery to pre-treatment streamflows occurred by year 9 in Eden 6 and by year 13 in Eden 5. This is not surprising given that forest regeneration was allegedly far more vigorous in Eden 6.

2.5.7 Comparative effects of uniform thinning and patch cutting

Jayasuriya *et al.* (1993) compared streamflow changes ensuing uniform thinning and patch cutting on two of the Black Spur catchments in the Maroondah basin. Both treatments resulted in a removal of about 50% of the forest basal area, and were applied to adjacent catchments with similar soils and rainfall. Initial streamflow increases were similar for both treatments (130-150 mm per year) but were more persistent for the uniform thinning treatment. In the case of the uniformly thinned catchment (Black Spur 3), a 15% streamflow difference was still evident 11 years after treatment, whereas streamflows had returned to pre-treatment levels in the patch cut treatment (Black Spur 1) after 5 years. Nandakumar and Mein (1993) have predicted that it will take 25 years for streamflows in Black Spur 3 (the patch cut treatment) to return to pre-treatment levels.

2.6 DIFFERENCE BETWEEN STREAMFLOWS FROM NATIVE EUCALYPT FORESTS AND PINE PLANTATIONS

In the preceding section, some reference was made to studies which compared streamflows from eucalypt and pine forested catchments. Almost all of the South African data suggests that streamflows from pine afforested catchments are *greater* than those from eucalypt afforested catchments (Bosch, 1979; Van Wyk, 1987; Smith and Scott, 1992; Dye, 1996; Scott and Smith, 1997), due to the relatively *higher* ET rates of eucalypts in South Africa. However, the opposite trend has been observed in Australia where higher ET rates are normally ascribed to pines, primarily because of their higher leaf area index and rainfall interception rates (Smith *et al.*, 1974; Pilgrim *et al.*, 1982; Dunin and Mackay, 1982; Cornish, 1989). Unlike in South Africa, pines generally seem to grow better than most eucalypt species in Australia.

Smith *et al.* (1974) compared rainfall interception and streamflow rates of pine (*P. radiata*) plantations and mixed species eucalypt forest at Lidsdale, NSW. They reported that the pine plantation generated lower streamflow than the eucalypt forest, primarily because of much higher rainfall interception rates in the pines. Similar findings for the same catchments were provided by Pilgrim *et al.* (1982) who used a more extensive data set than Smith *et al.* (1974). Pilgrim *et al.* (1982) argued that the streamflow differences between the two catchments could be entirely explained by differences in rainfall interception (Table 2.I).

TABLE 2.I DIFFERENCES IN THE MEAN ANNUAL WATER BALANCE BETWEEN A PINE PLANTATION AND A EUCALYPT FOREST AT LIDSDALE, NSW, OVER THE PERIOD 1974-1976 (AFTER PILGRIM *ET AL.* 1982).

Parameter	**Pine plantation**	**Eucalypt forest**
Rainfall (mm)	842	870
Rainfall interception (mm)	183	99
Transpiration and soil evaporation (mm)	472	501
Soil moisture change (mm)	-3	1
Streamflow (mm)	190	269

Dunin and Mackay (1982) compared the rainfall interception and transpiration rates of pine plantations (*P. Radiata*) and eucalypt (*E. Maculata*) forests in south east region of NSW under conditions of abundant soil moisture and similar radiation input. They found that pines transpired at a greater rate than eucalypts during winter, but that the annual transpiration totals for the two forest types were similar. However, the rainfall interception rates of pines were determined to be three to four times greater than those measured for the eucalypts. Dunin and Mackay (1982) found that the pines intercepted about 10% more of rainfall than the eucalypts.

Similar findings were reported by Feller (1981), who compared throughfall, stemflow and interception rates of two eucalypt species *(E. Regnans and E. Obliqua*) with those for pine (*P. Radiata*) plantations in the Maroondah catchment. He found that the pines intercepted 25.5% of gross rainfall over a two-year period (Table 2.J), compared to values of 18.5% and 15% for *E. Regnans* and *E. Obliqua* forest, respectively.

TABLE 2.J COMPARATIVE RATES OF THROUGHFALL, STEMFLOW AND INTERCEPTION IN EUCALYPT FORESTS AND PINE PLANTATIONS IN THE MAROONDAH BASIN, EXPRESSED AS A PERCENTAGE OF GROSS RAINFALL OVER A TWO-YEAR PERIOD (DATA FROM FELLER 1981).

Parameter	***E. Regnans***	***E. Obliqua***	***P. Radiata***
Throughfall (%)	74.5	84.5	73.5
Stemflow (%)	7.0	0.5	1.0
Interception (%)	18.5	15.0	25.5

Summarising several studies from Australia and New Zealand, Cornish (1989) ranked a range of factors affecting evapotranspiration rates in pine plantations, eucalypt forests and pastures (Table 2.K). His findings support those reported above, namely that pines and eucalypts seem to be differentiated mainly by rainfall interception rate. He ascribed enhanced interception rates in pines not only to higher leaf area index, but also to the lower albedo of pines, meaning that more net radiant energy is available to drive the evaporation process. A similar argument was made by Dunin and Mackay (1982).

TABLE 2.K RANKING OF FACTORS AFFECTING EVAPOTRANSPIRATION RATES IN PINE PLANTATIONS, EUCALYPT FOREST AND PASTURE (AFTER CORNISH 1989).

Characteristic	Ranking
Transpiration	Eucalypt = Pine > Pasture
Interception	Pine > Eucalypt >> Pasture
Available energy for evaporation (albedo)	Pasture > Eucalypt > Pine
Energy input (combined albedo and temp. profile)	Pine = Eucalypt > Pasture
Evapotranspiration (combined effects)	Pine > Eucalypts >> Pasture

Cornish (1989) estimated the streamflow reductions likely to arise from afforestation of pasture by pine plantations and eucalypt forest as a function of mean annual rainfall (Figure 2.H). Figure 2.H shows that because of the higher rainfall interception rate of pines, streamflow differences between pine and eucalypt afforested catchments can be expected to increase as mean annual rainfall increases.

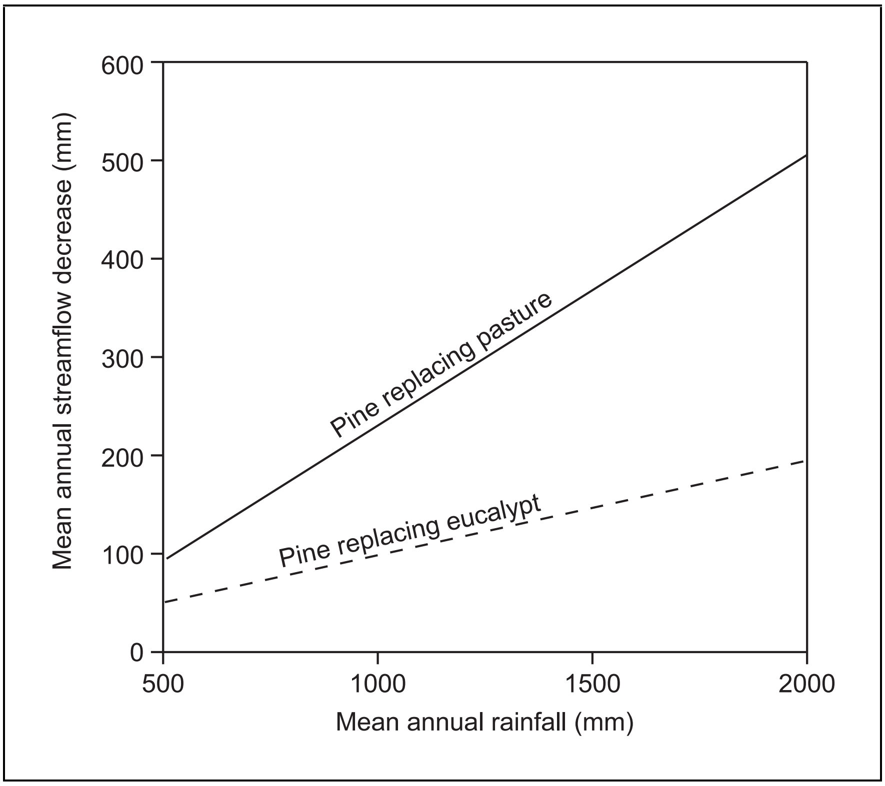

FIGURE 2.H ESTIMATED STREAMFLOW REDUCTIONS LIKELY TO ARISE FROM AFFORESTATION OF PASTURE CATCHMENTS WITH PINES AND EUCALYPTS, AS A FUNCTION OF MEAN ANNUAL RAINFALL (AFTER CORNISH 1989).

2.7 EFFECT OF FOREST AGE ON STREAMFLOWS

Australian forest hydrology is distinguished by a concern for the effect of forest age on streamflow. Within Australia there is some acceptance of the notion that regrowth forests yield less streamflow than old growth forests, because of differences in ET, yet this trend has only been verified for two forest areas in Australia (Maroondah and Karuah) and in some pine plantations in South Africa. Leaf area and ET measurements in a third forest catchment in Australia (Yambulla) suggest that forest age *could* affect streamflows, though there is no hydrometric evidence to back up this hypothesis. Below, we review the data supporting a link between forest age and streamflow.

2.7.1 Mountain ash forest

The most comprehensive understanding of forest age on streamflows in Australia is based on the mountain ash forests of Maroondah catchments in the central highlands of Victoria. Multiple catchment treatment experiments (Langford and O'Shaughnessy, 1977; Langford and O'Shaughnessy, 1980; Watson *et al.*, 1998) have been complemented by a large body of local process studies aimed at elucidating the process of evapotranspiration through the mountain ash forest life cycle (Dunn and Connor, 1993; Jayasuriya *et al.*, 1993; Vertessy *et al.*, 1995; Haydon *et al.*, 1996; Watson and Vertessy, 1996; Vertessy *et al.*, 1997; Vertessy *et al.*, 1998). The Maroondah catchments are fully forested, mainly with the mountain ash (*E. Regnans*) species, and are characterised by high rainfall (1200-2500 mm per year), and a cool, montane climate. These catchments are renowned for their deep and permeable soils which result in a strong dominance of baseflow in catchment runoff. The ecology of mountain ash forests is very distinctive, in that they regenerate prolifically after severe wildfire which kills the trees and produces a heavy seedfall. These forests are thus usually even-aged and monospecific, and tend to live for several hundreds of years unless they are killed earlier by wildfire. Significantly, the species thins naturally over time, resulting in major changes in forest structure and hydrologic function as stands age (Watson and Vertessy, 1996; Vertessy *et al.*, 1998).

Based on a large body of streamflow data, Langford (1976) developed relationships linking streamflow from mountain ash catchments to forest age. Kuczera (1985) built upon this by developing an idealised curve describing the relationship between mean annual streamflow and forest age for mountain ash forest (Figure 2.I). 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:

- the mean annual runoff from large catchments covered by pure mountain ash forest in an old-growth state is about 1195 mm;
- after burning and full regeneration of the mountain ash forest with young trees, the mean annual runoff reduces rapidly to 580 mm by age 27 years;
- after age 27 years, mean annual runoff slowly returns to pre-disturbance levels, possibly taking as long as 150 years to recover fully.

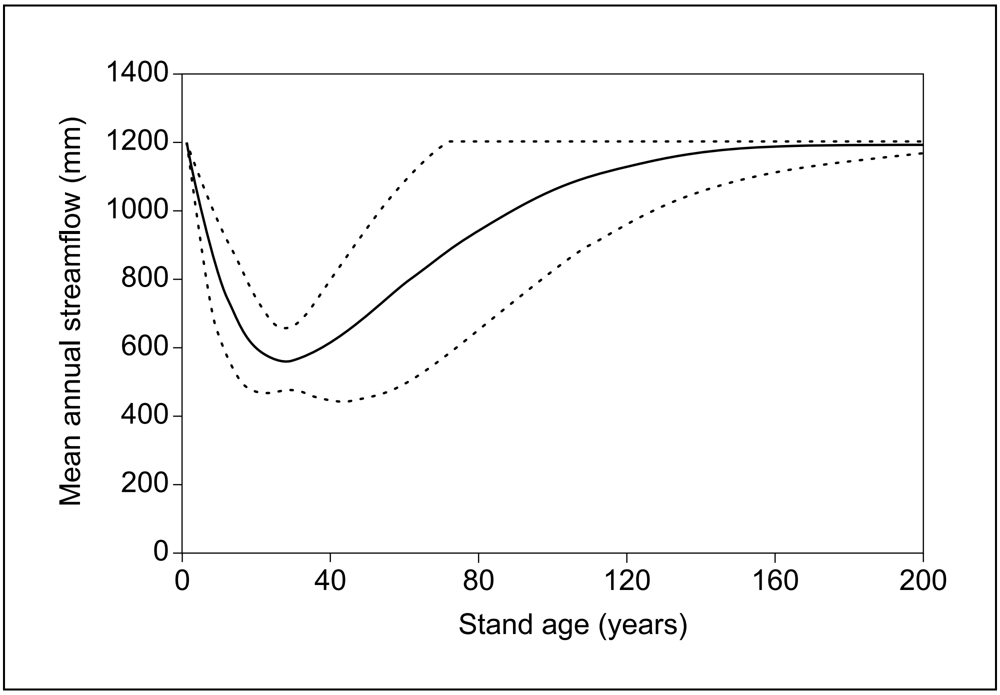

FIGURE 2.I RELATIONSHIP BETWEEN FOREST AGE AND MEAN ANNUAL RUNOFF FROM MOUNTAIN ASH FOREST CATCHMENTS (AFTER KUCZERA 1985).). DOTTED LINE DENOTES THE 95% CONFIDENCE LIMITS ON THE RELATIONSHIP.

The ‘Kuczera curve’ has three major deficiencies which should be noted. Firstly, the relationship fails to recognise the *increase* in catchment runoff that occurs for the first 4-6 years after forest clearance (Nandakumar and Mein, 1993; Watson *et al.*, 1998). This increase could not be detected in the large basins examined by Langford (1976) and Kuczera (1985), but has been noted in most small catchment studies in the Maroondah area (Langford and O’Shaughnessy, 1977). Secondly, the curve has wide error bands associated with it, particularly for forests aged between 50 and 120 years (Figure 2.I), so it is difficult to accurately predict when water yields will recover after disturbance. Thirdly, the curve is a generalised one, masking the great deal of variation that exists 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.

To emphasise this last point, Figure 2.J shows the streamflow response of the Picaninny catchment to a 78% clearfell in 1972. The shape of the streamflow response is similar to that predicted by the Kuczera curve, though the magnitude of response is significantly less because of the lower mean annual rainfall for this catchment (~1200 mm, rather than the 1950 mm assumed in the Kuczera curve).

Vertessy *et al.* (1998) provided a mechanistic explanation for the ‘Kuczera curve’ by elucidating leaf area and evapotranspiration dynamics in mountain ash forests of various ages. Their breakdown of the mountain ash water balance for the 1800 mm isohyet, and the manner in which it changes through time, is depicted in Figure 2.K.

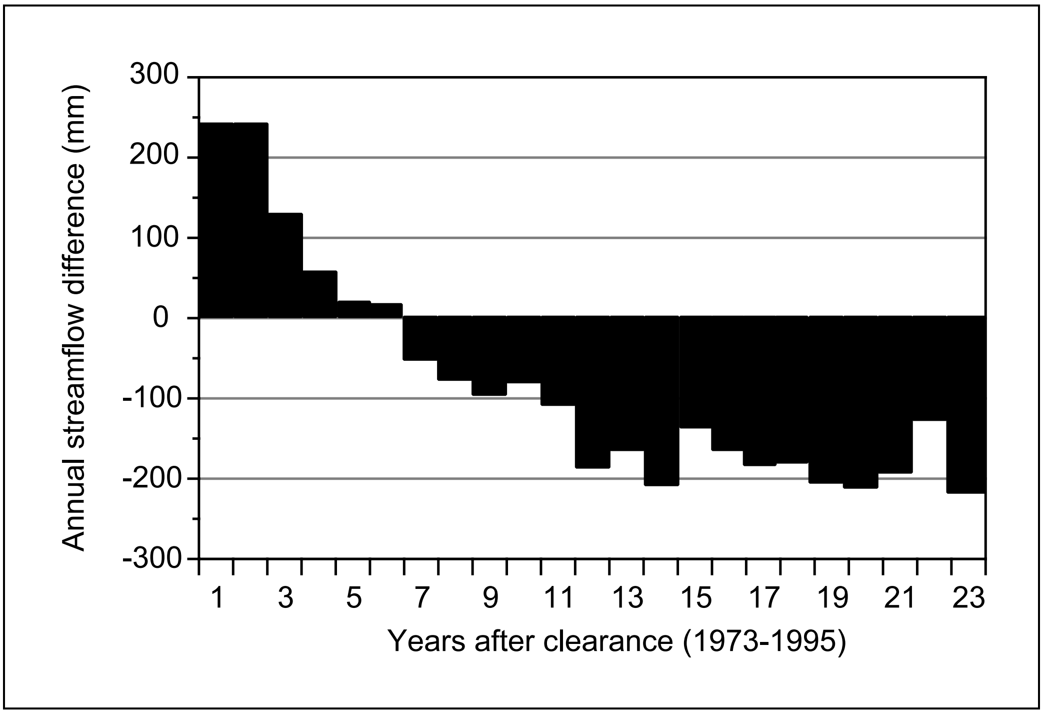

FIGURE 2.J ANNUAL STREAMFLOW CHANGE FROM THE PICANINNY CATCHMENT, VICTORIA, FROM 1973 TO 1995 (AFTER VERTESSY ET AL. 1998). THE CHANGES SHOWN ARE RELATIVE TO STREAMFLOWS FROM THE UNDISTURBED SLIP CREEK CATCHMENT, SITED ADJACENT TO PICANINNY.

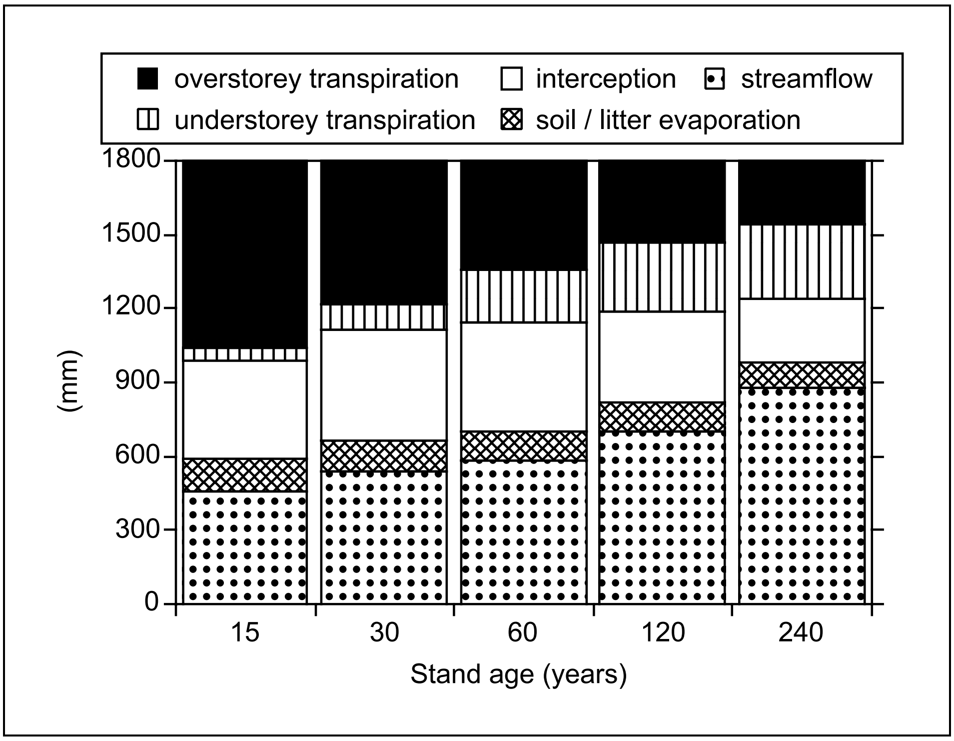

FIGURE 2.K WATER BALANCE FOR MOUNTAIN ASH FOREST STANDS OF VARIOUS AGES, ASSUMING ANNUAL RAINFALL OF 1800 MM (AFTER VERTESSY ET AL. 1998).

Vertessy *et al.* (1998) noted the following:

- overstorey (mountain ash) leaf area index (LAI) declines from 3.8 at age 15 years to 1.2 at age 240 years;
- understorey LAI increases from 0.4 at age 15 years to 2.4 at age 240 years, thus partially offsetting overstorey LAI declines with age;
- hence, total forest LAI declines from 4.2 at age 15 years to 3.6 at age 240 years;
- however, transpiration per unit area of leaf in the understorey is only 63% of that measured for overstorey;
- 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 on overstorey transpiration over the same period;
- 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; and,
- 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.

Using the small catchment experimental data yielded from the Maroondah basin study, Watson *et al.* (1998) developed an alternative forest age-streamflow relationship (Figure 2.L). It differs from the Kuczera curve in the following respects:

- it incorporates *increases* in streamflow which have been observed to occur in the first few years after forest clearance;
- the maximum streamflow reduction is about 100 mm *less* than indicated by the Kuczera curve;
- the rate of streamflow recovery is much more gradual, even though it returns to pre-treatment level in the same length of time;
- it is specific to the Maroondah catchments, rather than generalised for a large region.

Watson *et al.* (1998) point out that their curve is ‘fitted by eye’, though is arguably just as legitimate as selecting any particular mathematical form to fit through sparse data points. They provide a rather awkward seven parameter equation that describes their alternative relationship, along with parameter values used to produce the curve shown in Figure 2.L.

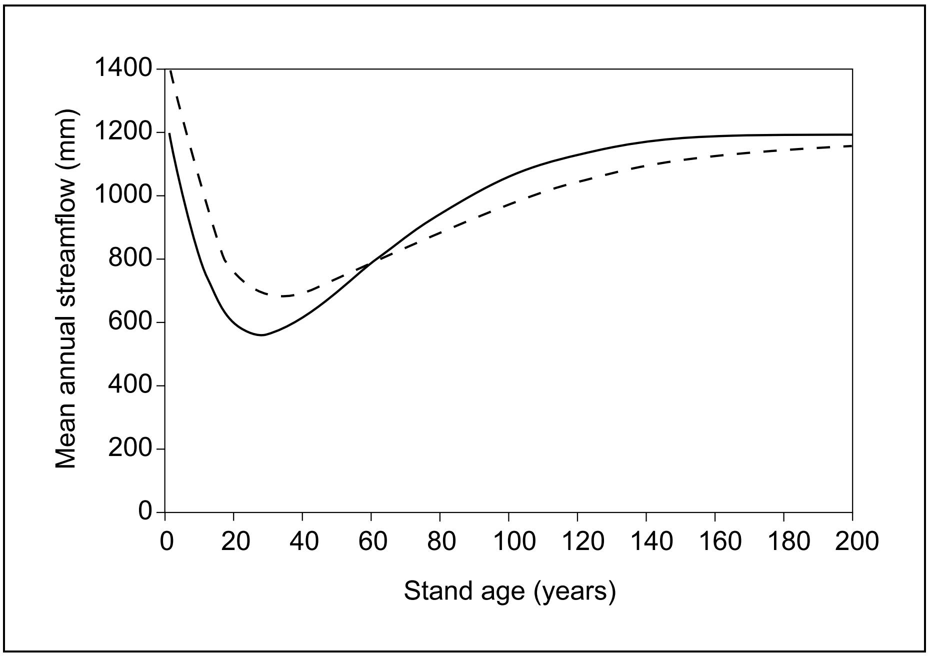

FIGURE 2.L AN ALTERNATIVE 'MODEL' OF THE STREAMFLOW-FOREST AGE RELATIONSHIP FOR MOUNTAIN ASH FORESTS (DASHED LINE) (AFTER WATSON ET AL. 1998). THE KUCZERA CURVE (SOLID LINE) IS SHOWN FOR REFERENCE.

2.7.2 The Karuah catchments

The only other Australian studies which have demonstrated a link between streamflow and forest age are those of Cornish (1993) and Cornish and Vertessy (1998). These studies are based on streamflow data from the moist eucalypt forests of the Karuah catchments in the lower north east region of NSW. They share some common features with the mountain ash forest catchments in Victoria, notably high annual rainfall (~1600 mm), highly productive, moist eucalypt stands, deep and permeable soils, and strong baseflow. Cornish and Vertessy (1998) analysed streamflow records for six catchments, logged to varying extents (25-79%). Their analysis is restricted to 7 pre-treatment and 14 post-treatment years of streamflow. Hence, the period of record is shorter than that underpinning the mountain ash forest record in Victoria.

Cornish and Vertessy (1998) showed that streamflows declined below pre-treatment levels seven years after logging in three of the six treated catchments, and declined in a regular manner over the next seven years. The other three treated catchments showed an initial decline in streamflows below pre-treatment levels around year 8, followed by a slight increase, then another decrease below pre-treatment levels. Cornish and Vertessy (1998) showed that these three catchments were affected by insect attack, leading to decreased leaf area and ET rates and enhanced streamflows.

Figure 2.M shows the average and range of streamflow changes caused by forest disturbance in the six treated Karuah catchments. It shows that the maximum decrease in annual streamflow is over 60 mm per 10% of forest area treated, which is similar to the maximum reductions noted for Victorian mountain ash forests. However, some of the Karuah catchments have shown a comparatively modest reduction in streamflow, meaning that the average reduction in streamflow is about 35 mm per year per 10% of forest treated by the end of the post-treatment

period of record. It is worth noting, however, that further streamflow reductions are likely in the future as the peak forest growth rate has probably not yet been attained in the Karuah catchments. Also, the catchments which have been affected by insect attack are likely to experience increased growth and further reduce streamflows.

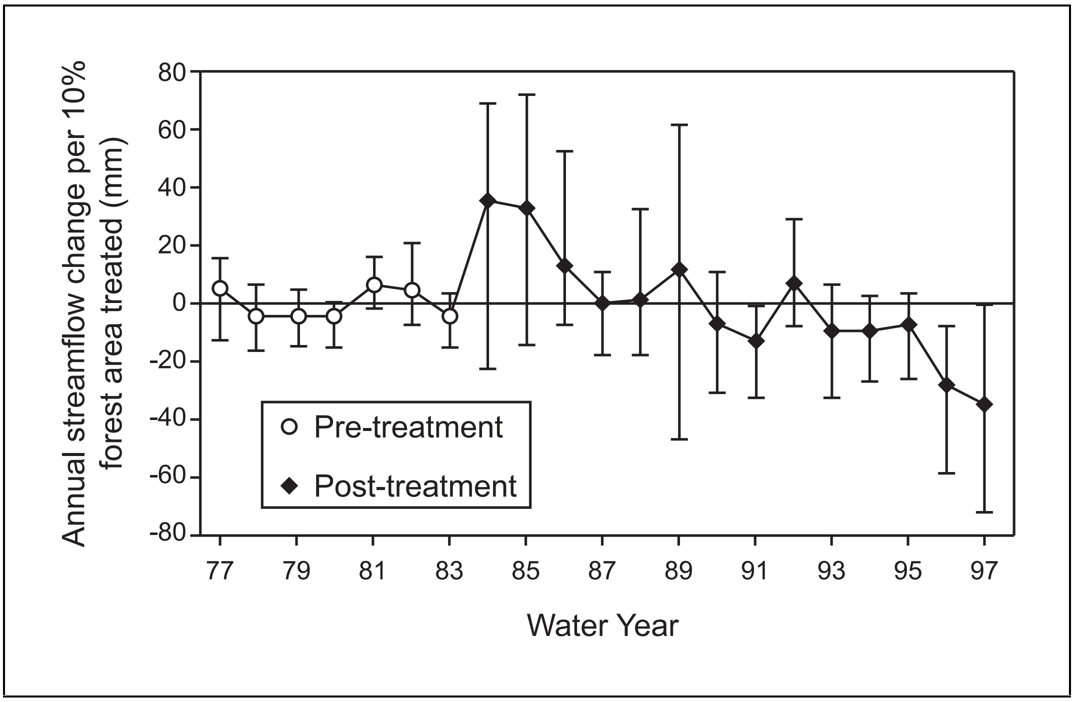

FIGURE 2.M : ANNUAL STREAMFLOW CHANGES AMONGST THE SIX TREATED KARUAH CATCHMENTS IN THE NSW LOWER NORTH EAST REGION (AFTER CORNISH AND VERTESSY 1998). ENDS OF BARS DENOTE MAXIMUM AND MINIMUM CHANGES, SYMBOLS DENOTE MEAN CHANGE.

Cornish and Vertessy (1998) related the magnitude of streamflow reductions in the Karuah catchments to mean annual basal area increase (an index of forest growth rate), soil depth (an index of soil water storage) and canopy cover (a crude index of rainfall interception and transpiration rate). They developed the following equation:

$$ASR = 1368 - 480.8*SD - 37.418*BAI - 16.76*CC \qquad (2)$$

where:

ASR = reduction in annual streamflow for the final year of record (mm)
SD = soil depth (m)
BAI = mean annual basal area increment
CC = canopy cover (%)

The model fit obtained by Equation 2 is shown in Figure 2.N. Equation 2 was shown to account for almost 82% of the variation in observed annual streamflow reductions, with soil depth being the most important explanatory variable in the equation. It is noteworthy that the Victorian mountain ash forest catchments have very deep soils.

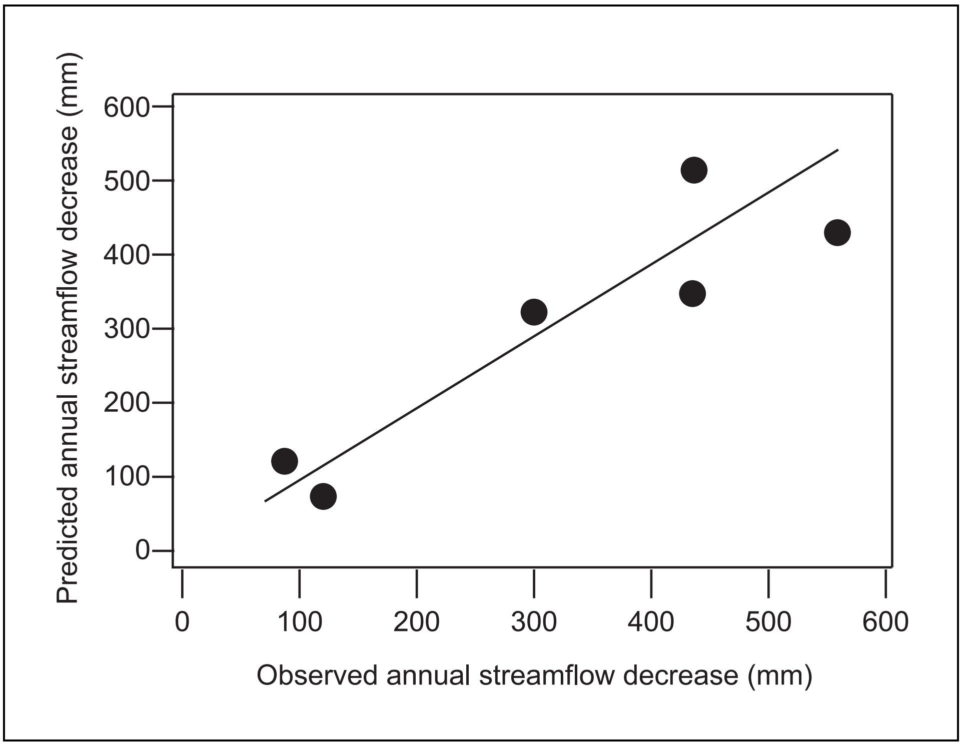

FIGURE 2.N OBSERVED AND PREDICTED REDUCTIONS IN ANNUAL STREAMFLOW FOR THE SIX TREATED KARUAH CATCHMENTS (AFTER CORNISH AND VERTESSY 1998). THE PREDICTIONS ARE BASED ON EQUATION 2 AND ASSUME THAT THE ENTIRE CATCHMENT AREA WAS TREATED.

2.7.3 The Yambulla catchments

Roberts *et al.* (1998) compared leaf area index and transpiration rates in *E. Sieberi* forest of different ages in the Yambulla State Forest, nearby but outside of the experimental catchments. Over a two-month period in summer, they determined that mean daily transpiration was 2.6, 1.5 and 0.7 mm for stands aged 14, 45 and 160 years, respectively. These differences were evident in spite of fairly similar leaf area indices amongst the three stands, leading the authors to suggest that ‘transpiration per unit leaf area’ declines with forest age. Similar trends have been measured but not yet published for mountain ash forests (Vertessy, unpublished data). These findings imply that streamflows should generally *increase* as the *E. Sieberi* forest ages.

Roberts (pers. comm.) has analysed streamflow data for the Eden 1, 5 and 6 catchments. Eden 1 is an undisturbed control catchment, whereas Eden 5 and 6 are the most heavily treated catchments, having been affected by both logging and wildfire over extensive areas. For the 18 years following disturbance and forest regeneration in these catchments, there is *no evidence that streamflows have reduced to below pre-treatment levels*, despite fairly vigorous regeneration of forest in Eden 6. Hence, there is no hydrometric evidence to support the contention of Roberts *et al.* (1998) that forest age affects the water balance of *E. Sieberi* catchments.

2.7.4 Pine plantations

There is no Australian data linking pine plantation age to the amount of streamflow from catchments, though some evidence is available from South Africa. Van Wyk (1987) showed that streamflow reductions in the pine afforested Bosboukloof catchment (relative to those from a grassland control catchment) changed through the life cycle of the plantation. Figure 2.O shows that peak reductions in streamflow from this catchment occurred around age 24-27 and declined significantly by age 36-39. This finding is consistent with hydrometric evidence from the mountain ash forests which indicates that streamflow minima are commonly attained when the forest is aged about 27 years. Ryan *et al.* (1997) summarised the world literature on the chronosequence of growth rates and stand leaf area for different forest species. They showed that peak forest growth rate can be attained anywhere between 3 and 68 years of age, depending on forest type and site conditions. They also showed that leaf area index (a major determinant of rainfall interception and transpiration rate) for most forest types tails off sharply after the time of peak growth rate has been passed. It thus follows that streamflows should increase as a forest or plantation ages.

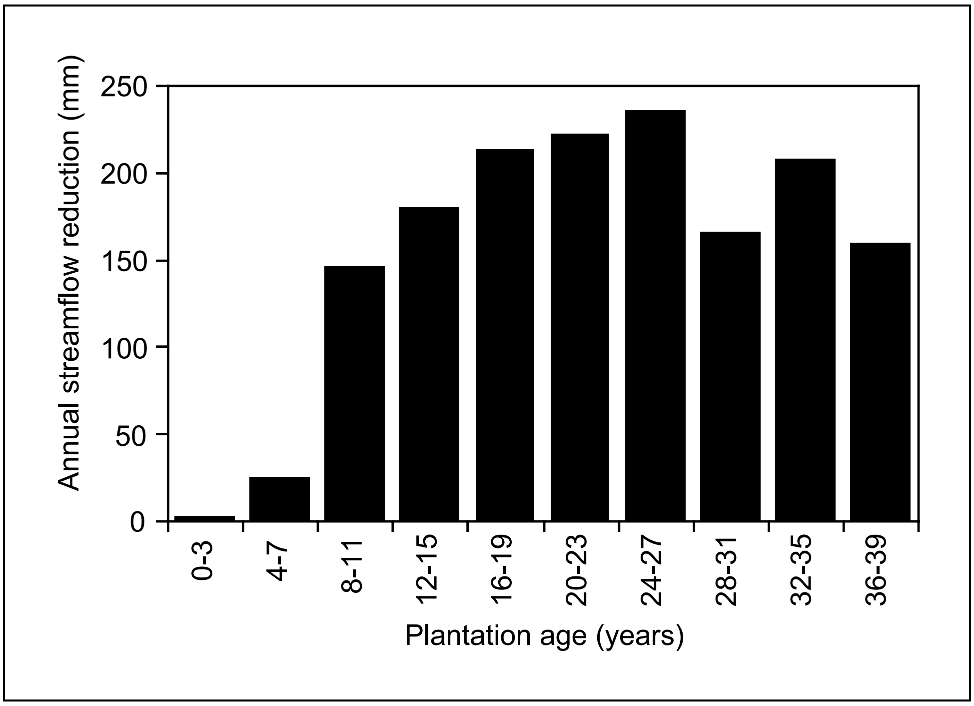

FIGURE 2.O TEMPORAL CHANGES IN STREAMFLOW REDUCTIONS IN THE PINE AFFORESTED BOSBOUKLOOF CATCHMENT IN SOUTH AFRICA, RELATIVE TO A GRASSLAND CONTROL CATCHMENT (DATA FROM VAN WYK 1987).

2.7.5 Applications of the Kuczera curve to other sites

The 'Kuczera curve' and variants thereof, have been used to predict temporal changes in annual streamflows in catchments other than those on which it is based. Moran (1988) used it to predict the water yield consequences of logging mountain ash and mixed eucalypt forests, as well as softwood plantations, in the Otway Ranges of south-western Victoria. She developed a methodology for coping with species other than mountain ash and for adapting the 'Kuczera curve' to different site conditions. Cornish (1997) adapted the 'Kuczera curve' significantly and applied it to the Rocky Creek Dam catchment in the lower north east region of NSW. He used his adapted model to predict streamflow changes ensuing from rotational logging and thinning of small coupes of various ages in a large basin. A major contribution of this study is that Cornish (1997) illustrated the importance of logging rotation cycles and the age of the forest being logged in determining the overall streamflow response of the basin. Generally speaking, the streamflow responses were much lower than might have been anticipated, because (a) streamflow declines following logging were significantly reduced if the logged forest was not old growth, and (b) under rotational forestry, streamflow reductions in regenerating coupes were partly off-set by streamflow increases in freshly logged areas.

2.8 EFFECT OF FORESTRY ACTIVITIES ON STREAMFLOW REGIME

Thus far, this review has focussed on forestry-induced changes in annual streamflows. However, catchment managers also need to know how the streamflow regime might change as a consequence of forestry activities. This is an important issue as the distribution of flows has important consequences for the security of water for downstream enterprises (in the case of low flows), and the safety of dams, roads, culverts and bridges (in the case of high flows). Almost all catchment studies have noted that low, median and high flows decrease as a consequence of afforestation, and increase as a result of forest clearance (Hewlett and Helvey, 1970; Burt and Swank, 1992; Schofield, 1996). What is unclear is whether low flows and high flows change by the same amount as annual flows, or whether part of the streamflow range is more affected than others.

It is worth pointing out here that the literature on forestry-induced changes to flow regime is fairly confusing. Some workers frame their analyses around monthly streamflow totals, while others focus on instantaneous flow rates or on flow rates of a particular duration (usually hourly or daily). Furthermore, the literature on this topic is riddled with subjective concepts such as 'low flows' and 'high flows' which appear to be defined in a variety of ways. All of these factors make it difficult to compare findings from various studies. Finally, sub-annual streamflows, particularly instantaneous flows, are much more variable between catchments (because of differences in soils and topography) and in time (because of climate variability) than annual streamflows, meaning that it is difficult to 'tease out' the effects of forestry on flow regime.

2.8.1 Effects of afforestation on low flows in South Africa

The most detailed insights into the effects of forestry on flow regime come from catchment afforestation studies undertaken in South Africa. This research has shown that afforestation in South Africa has reduced all flows but that low flow reductions are relatively greater than reductions in annual flows (Bosch, 1979; Bosch and von Gadow, 1990; Smith and Scott, 1992; Scott and Smith, 1997).

Bosch and von Gadow (1990) compared mean monthly streamflows for the Cathedral Peak catchment in South Africa, prior to and after afforestation of grasslands with pines (Figure 2.P). They demonstrated that absolute reductions in streamflow were greatest during the wet months, but that the reductions were *relatively* greatest during the low flow periods. For example, Figure 2.P shows the streamflows in March (a wet month) are reduced by about 30% as a consequence of afforestation, but are reduced by over 60% in October (a dry month). They attributed this trend to the fact that grasses are dormant during the low flow periods and thus do not transpire. Bosch and von Gadow (1990) noted that streamflow reductions were relatively uniform throughout the year when pines replaced indigenous scrub vegetation which was also evergreen and thus active during the low flow periods. An interesting feature of Figure 16 is that monthly streamflow differences were smallest during the period following peak monthly streamflow (April-July). Presumably, abundant soil moisture is present in the system during this time, enabling the grasses to transpire at relatively high rates. These reserves are probably depleted from September onwards, resulting in diminishing grass ET and thus larger differences between grass and plantation streamflows.

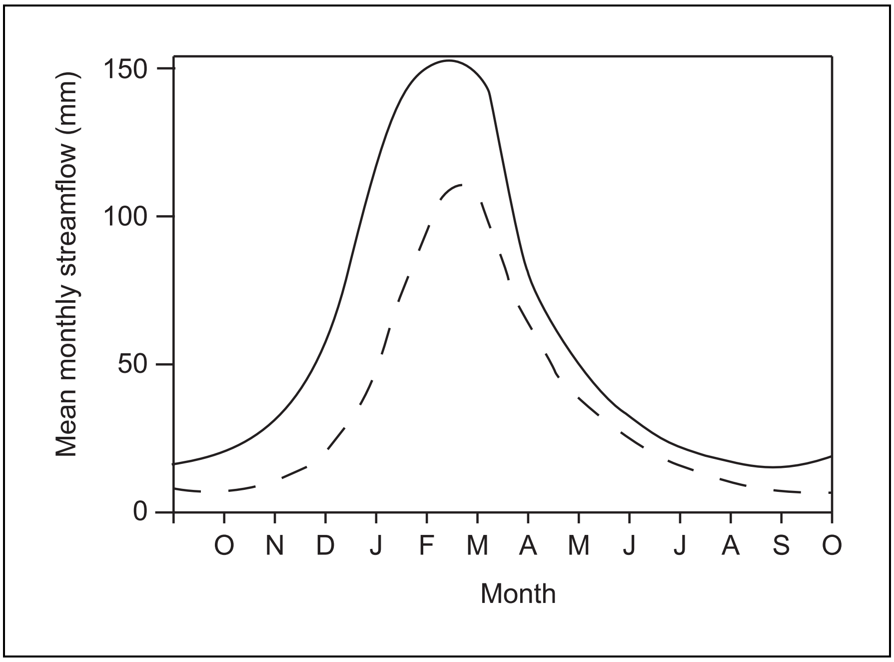

FIGURE 2.P MEAN MONTHLY STREAMFLOWS IN THE CATHEDRAL PEAK CATCHMENT, SOUTH AFRICA, BEFORE AND AFTER AFFORESTATION OF THE GRASSLAND VEGETATION WITH PINES (AFTER BOSCH AND VON GADOW 1990). SOLID (UPPER) LINE DENOTES GRASSLAND CONDITION, DASHED (LOWER) LINE DENOTES PINE PLANTATION CONDITION.

Scott and Smith (1997) summarised a large amount of streamflow data from five afforestation experiments, comprising nine catchments sited throughout South Africa. They compared reductions in annual streamflows and low flows ensuing from afforestation of grasslands with pines and eucalypts. They also compared results from sites considered to be ‘optimal’ and ‘sub-optimal’ for the growth of these two forest types. ‘Low flows’ were defined as the three driest months of an ‘average’ year, or more specifically, as those below the 75th percentile of monthly flows. ‘Optimal’ sites were regarded as those with deep soils and a sub-tropical climate, whereas the ‘sub-optimal’ sites were regarded as those with shallow soils and cooler mountain climates. Scott and Smith (1997) fitted eight different empirical models of sigmoidal form to the data, seven of which had r^2 values exceeding 0.95. The worst model fit had an r^2 value of 0.89. These eight models were used to predict the percentage reduction in annual and low flows for pines and eucalypts growing under optimal and sub-optimal conditions as a function of time after afforestation (Figure 2.Q).

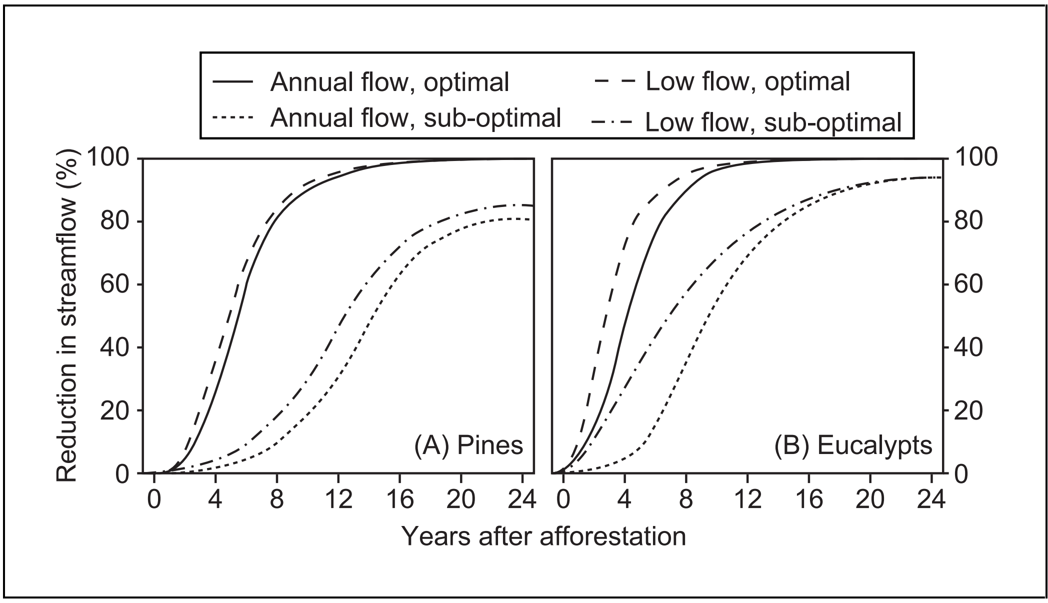

FIGURE 2.Q GENERALISED CURVES FOR PREDICTING ANNUAL AND LOW REDUCTIONS AS A FUNCTION OF AGE IN PINE AND EUCALYPT PLANTATIONS IN SOUTH AFRICA (AFTER SCOTT AND SMITH 1997). SEPARATE CURVES ARE SHOWN FOR OPTIMAL AND SUB-OPTIMAL GROWING REGIONS FOR BOTH FOREST TYPES.

Figure 2.Q shows that the effects of afforestation on annual and low flows were less pronounced for pines than for eucalypts, a finding highlighted earlier in this review. However, flow reductions were far less pronounced for both forest types when ‘sub-optimal’ sites were afforested. For the ‘optimal’ sites, streamflows changed from perennial to intermittent after about nine years in the case of eucalypt afforested catchments, and after about 14 years in the pine afforested catchments. However, at the ‘sub-optimal’ sites, annual and low flows persisted through the plantation life-cycle for both forest types, though these were most reduced (~95%) in the case of the eucalypt afforested catchments. Figure 2.Q shows that low flows were reduced relatively more than annual flows, particularly in the case of eucalypts. These differences were amplified in the case of ‘sub-optimal’ sites, particularly in the early life of the eucalypt plantations.

2.8.2 Effects of afforestation on flood peaks in New Zealand

Fahey and Jackson (1997) showed that the conversion of tussock grasslands to pine plantations in the Glendhu catchments of South Island, New Zealand resulted in uniform decreases in flood peaks across the entire range of streamflows. They plotted the frequency distribution of mean flood peaks for four different size classes of storms, for discrete three-year periods before and after afforestation (Figure 2.R). Figure 2.R compares the mean flood peak for each storm size class for the control catchment (G1) and the afforested catchment (G2), prior to afforestation and after canopy closure of the plantation. Mean flood peaks for each storm size class were similar in both catchments prior to afforestation. After plantation canopy closure, mean flood peaks were reduced by about 60% in all four storm size classes in the afforested G2 catchment. Fahey and Jackson (1997) also showed that low flows decreased as a result of afforestation in the Glendhu catchments, but they do not provide an analysis to suggest that they changed by a different rate when compared to high flows.

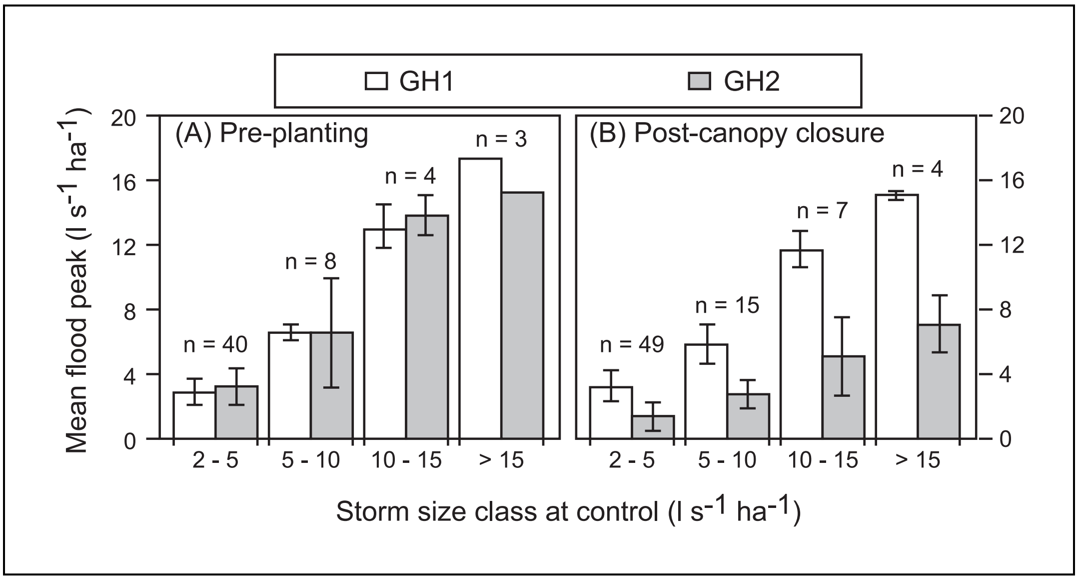

FIGURE 2.R COMPARISON OF MEAN FLOOD PEAKS FOR FOUR SIZE CLASSES OF STORMS IN THE G1 (CONTROL) AND G2 (TREATED) CATCHMENT, (A) PRIOR TO THE TREATMENT OF G2, AND (B) AFTER PLANTATION CANOPY CLOSURE IN G2 (AFTER FAHEY AND JACKSON 1997). BARS DENOTE ONE STANDARD DEVIATION ON EACH MEAN VALUE, N DENOTES THE NUMBER OF STORMS IN EACH CLASS

2.8.3 Clearance and regeneration of moist eucalypt forest

Compared to South Africa and New Zealand, there is little evidence to support systematic changes in flow regime as a consequence of forestry activities in Australian catchments. Some relevant Australian data are available from the Victorian mountain ash forest and Karuah studies (Haydon, 1993; Watson *et al.*, 1998; Cornish and Vertessy, 1998). These show the usual pattern of increased low, median and high flows in the immediate post-logging period and a recovery to pre-treatment levels once regeneration is established. In cases where old growth forest is replaced by vigorous regrowth, all flows are shown to decrease. There is some evidence for changes in the pattern of flow regime, but this is equivocal.

Haydon (1993) examined forest thinning-induced changes in flow regime of the Crotty Creek catchment, a mountain ash forested basin located near the Maroondah group. This 122 ha catchment consisted of 1939 regrowth and was thinned *over a six year period* to 50% of its basal area using a strip thinning pattern. Haydon (1993) compared average monthly flows from a three year pre-treatment period and a four year post-treatment period, commencing in the year after thinning had been completed (1985). As expected, he found that mean annual streamflow increased (by about 290 mm), and that flows of all magnitudes increased. However, he noted that the *rate* of change was not consistent across all months, and that a more uniform flow regime developed (Figure 2.S). Figure 2.S shows that some of the ‘wet’ months (June-September) yielded a reduced share of annual streamflow immediately after thinning, whereas some of the ‘dry’ months (December-February) yielded an increased share. Haydon (1993) did not provide a convincing interpretation for this phenomenon, so further investigation of it is warranted.

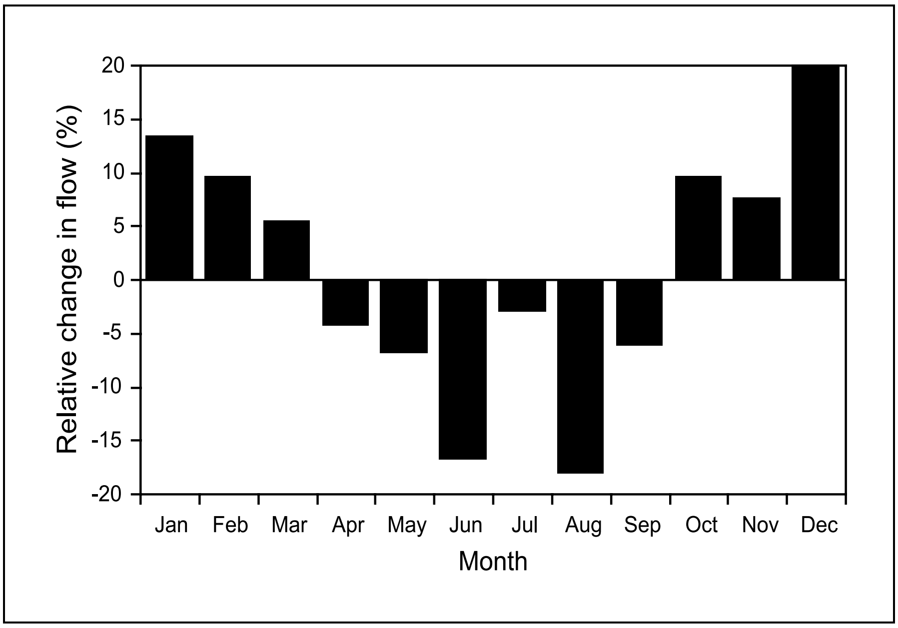

FIGURE 2.S EFFECT OF A 50% BASAL AREA THINNING ON MONTHLY STREAMFLOWS IN THE CROTTY CREEK CATCHMENT, VICTORIA (DATA FROM TABLE 6.1 IN HAYDON 1993). TO DE-EMPHASISE THE EFFECTS OF STREAMFLOW VARIABILITY, MONTHLY STREAMFLOW IS EXPRESSED AS A PERCENTAGE OF ANNUAL STREAMFLOW. POSITIVE VALUES DENOTE AN ENHANCED SHARE OF STREAMFLOW IN THE POST-TREATMENT PERIOD, WHEREAS NEGATIVE VALUES DENOTE A REDUCED SHARE. THE VALUES SHOWN ARE AVERAGES TAKEN OVER A 3-4 YEAR PERIOD.

Watson *et al.* (1998) provided flow duration curves for three control catchments and five treated catchments in the mountain ash forested Maroondah basin in Victoria. For each catchment, separate curves were provided for the complete pre-treatment period and for multiple post-treatment ‘blocks’ of five year duration. In the ‘wetter’ Monda and Myrtle catchments (annual rainfall > 1600 mm), streamflows of all magnitudes increased uniformly immediately after forest clearance, then declined as regeneration commenced, again in unison. However, in the ‘drier’ Picaninny catchment (annual rainfall < 1200 mm) low flows were more severely reduced than median or high flows, particularly in the later stages of forest regeneration. To illustrate this finding, the flow duration curves for Picaninny, and it’s control catchment Slip Creek, are presented in Figure 2.T. When assessing the flow regime changes at Picaninny, as illustrated in Figure 2.T(a), it is necessary to compare them with rainfall-induced changes evident in the flow duration curves for Slip Creek, shown in Figure 2.T(b). An important conclusion of the Watson *et al.* (1998) study was that the effects of inter-annual rainfall variability tended to overwhelm the subtle flow regime changes caused by forest clearance and regeneration.

Cornish and Vertessy (1998) showed that flows of all magnitudes increased in the period immediately following logging in the Karuah catchments. During this time, high flows tended to increase most, particularly in catchments that had thinner soils and higher levels of disturbance. By the time vigorous regrowth forest was established in the catchments, all flows had returned to pre-treatment levels, though low flows declined *below* pre-treatment levels in the catchments which experienced the greatest annual streamflow changes. However, no such low flow reductions were evident in the catchments with thin soils. Overall though, Cornish and Vertessy (1998) attributed most annual streamflow changes in the Karuah catchments to changes in baseflows.

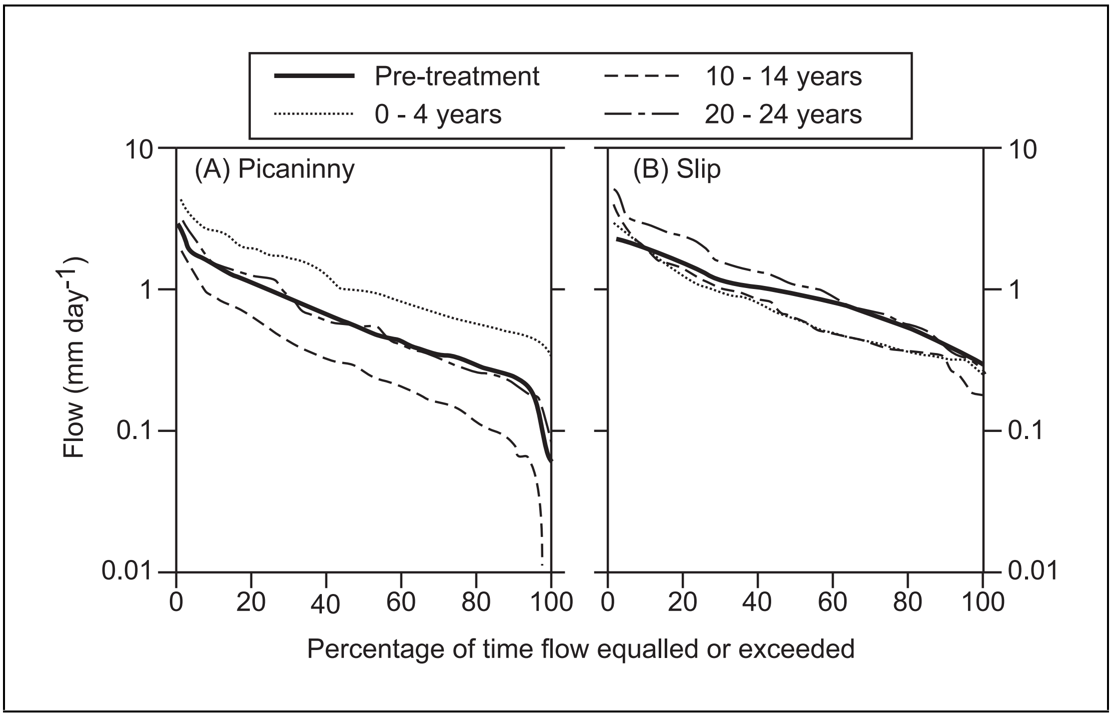

FIGURE 2.T FLOW DURATION CURVES FOR THE PICANINNY AND SLIP CREEK CATCHMENTS, MAROONDAH BASIN, VICTORIA (AFTER WATSON ET AL. 1998). SEPARATE CURVES ARE SHOWN FOR THE PRE-TREATMENT PERIOD AND DISCRETE FIVE-YEAR BLOCKS IN THE POST-TREATMENT PERIOD; ONLY A SUB-SET OF THE ORIGINAL DATA ARE SHOWN HERE FOR CLARITY. SLIP CREEK IS AN UNDISTURBED CONTROL OF OLD GROWTH MOUNTAIN ASH FOREST. PICANINNY WAS CONVERTED FROM OLD GROWTH TO REGROWTH MOUNTAIN ASH OVER 78% OF ITS CATCHMENT AREA.

There is no published evidence of forestry-induced flow regime changes for the Yambulla group of catchments, though Mackay and Cornish (1983) do compare storm hydrographs for undisturbed control catchments and catchments which were burnt and logged. They noted that peak flows and stormflow volumes increased as a consequence of high intensity burning, and were increased further after post-fire salvage logging of timber. They attribute these increases to reductions in ET, but also to reductions in soil infiltration capacity due to soil compaction by logging machinery.

2.9 FACTORS WHICH COULD ALTER THE EXPECTED IMPACTS OF FOREST DISTURBANCE ON STREAMFLOW

There are several factors which might cause catchments to respond to forest disturbance in unexpected ways. Indeed, these factors help explain the high variability evident in pooled catchment treatment experiment data sets (Bosch and Hewlett, 1982; Stednick, 1996). Some such factors are described briefly below.

2.9.1 Insect attack and defoliation

Bethlahmy (1974) showed that bark beetle epidemics affected long-term streamflow records in two forested basins in Colorado, USA. Mean annual streamflows increased by 24 and 32% over a 25 year period, relative to an undisturbed catchment nearby. Watson *et al.* (1998) reported that insect attack of the forest canopy dramatically altered the streamflows in the Monda group of mountain ash forest catchments in the Maroondah basin. Separate attacks in 1988 and 1996 partly defoliated the forest and reduced ET rates, leading to increases in streamflow. These attacks occurred in the early life of a regenerating forest (the Monda group were clearfelled in 1977), altering expected patterns of forest growth and water balance dynamics in those catchments. Similar insect attacks were reported by Cornish and Vertessy (1998) for the Karuah group of catchments. Such attacks significantly changed the expected response of two of the six treated experimental catchments in that group. In both the Karuah and Monda examples referred to here, the effects were transient, lasting between 2 and 5 years.

2.9.2 Variable forest regeneration

Some catchment treatment experiments are confounded by variation in vegetation response to disturbance. The vigour of forest regeneration is affected by soil conditions and the rainfall pattern following the forest disturbance event, so variability between catchments and through time can be expected. Watson *et al.* (1988) noted that poor regeneration of mountain ash forest in the Picaninny catchment delayed growth and altered streamflow response over the first few years following logging. Similarly, Cornish and Vertessy (1998) attributed inter-catchment differences in post-logging streamflow response to differences in the forest regeneration rate amongst the Karuah group of catchments.

2.9.3 Fire

A distinctive feature of Australian eucalypt forests is that their species composition and structure is controlled by fire. Fire frequency and intensity impact on the manner of forest regeneration can thus have important hydrologic consequences. The Yambulla catchment experiments in the south east region of NSW were initially conceived to assess the impacts of logging. However, after some initial logging treatments, a wildfire occurred and affected most of the catchments. These fires altered the composition of the forest and, to a lesser extent, the soil hydraulic properties, of each catchment in a variable manner as the burn intensity and coverage was variable. Hence it is difficult to isolate the hydrologic effects of logging from fire in the Yambulla experiments.

2.9.4 Interaction with shallow groundwater in the south west Jarrah forests

The response of catchments to Jarrah forest clearance in south west Australia is often complicated by interactions with shallow groundwater systems. As has been observed elsewhere, forest clearance in these catchments results in reduced ET and thus enhanced streamflow. However, many of these catchments are also coupled to shallow groundwater systems, and several studies have shown that this leads to an altered hydrologic response to forest disturbance (Ruprecht and Schofield, 1989; Ruprecht and Schofield, 1991; Ruprecht and Stoneman, 1993; Stoneman, 1993; Schofield, 1996). These studies show that groundwater recharge increases when ET is reduced and that, under certain circumstances, groundwaters can rise enough to reach the surface in valley bottoms. This has the effect of dramatically increasing the runoff producing area in these catchments, leading to increases in rainfall/runoff ratios which are proportionally greater than reported elsewhere. For instance, Ruprecht and Schofield (1989) showed that annual streamflow increased from 11 to 32% of annual rainfall over a 10 year period in a cleared Jarrah forest catchment. This rise was shown to be coincident with the expansion of the groundwater discharge area from 4 to 20% of the catchment area. Another feature of these catchments is that the time taken for a new hydrologic equilibrium to be reached is longer than normal as groundwater systems tend to adjust slowly (Ruprecht and Schofield, 1989; Stoneman, 1993).

2.10 KNOWLEDGE GAPS AND RECOMMENDATIONS FOR FURTHER WORK

There are several areas demanding further research before the impacts of forestry on streamflows can be properly understood and forecast in Australia.

A greater number of studies are needed which compare the water balance of old growth and regrowth eucalypt forests. The dynamics of mountain ash are now well understood but a similar knowledge base is required for other eucalypt communities. Process studies such as those conducted by Vertessy *et al.* (1998) are recommended to elucidate the streamflow-age relationships observed in the Karuah group of catchments (Cornish and Vertessy 1998). Recent field measurements by Sandra Roberts (University of Melbourne) and Rob Vertessy (CSIRO) indicate that transpiration per unit leaf area declines with forest age in both *E. Sieberi* and *E. Regnans* forests. These trends need to be verified in the forests where they were determined and investigated in other eucalypt communities.

Almost all of the data reported in this review are of an empirical nature. Such data underpins our knowledge of how catchments respond to forest disturbance but is compromised by significant inter-site variability. There are real difficulties in extrapolating empirical relationships between sites with different physical characteristics (climate, topography, soils and vegetation). In recent years there have been significant advances made in process-based hydrologic modelling of forest catchments (Vertessy *et al.,* 1993; Vertessy *et al.,* 1996; Watson *et al.,* 1997; Watson *et al.,* 1998). This new generation of models enable site factors to be taken into account in a way that is not possible with empirical models. However, before they can be used, a quantum leap is needed in the way that we collect environmental data, needed to drive these models. Accurate maps of forest age, forest type, soil type and soil depth are still surprisingly difficult to obtain, as are good temporal sequences of rainfall, humidity, temperature and radiation. Such data are critical if process-based models are to be employed to forecast the impacts of forest disturbance and climate change on streamflow.

This review has highlighted the lack of Australian reports on seasonal changes in streamflow resulting from forestry activities. Raw data is widely available to evaluate forestry-induced changes in flow regime, and it is recommended that appropriate analyses are conducted to test for such changes across a range of catchments. One particularly useful application of process-based models that should be explored is the simulation of changes to flow frequency spectra that result from forestry activities. Process-based models, if properly calibrated on a site, can be used to predict how flows of varying magnitudes may be differentially altered by changed forest cover. If these models also have a forest growth component embedded in them (as in the model described by Vertessy *et al.* 1996) then the persistence and transience of these changes in streamflow spectra can also be ascertained. Even more importantly, the effects of variable climate (droughts and floods) can also be estimated. These may well have an over-riding influence on streamflow dynamics when compared to the effects of forest cover and forest age.

Finally, whilst Australia has several good paired catchment experiments, few of these are set up to properly compare water balance differences between varying landuses. For instance, there are very few well instrumented cropping, pasture and pine plantation catchments in Australia that are proximal to one another. Given the likelihood that Australian grazing and cropping lands will undergo extensive afforestation in the next three decades (DPIE, 1997), it is essential that we establish a range of sites throughout the country to measure the water balance differences between cropped, grazed and afforested catchments. There is a particular need to establish such comparative sites in areas of intermediate rainfall (700-1400 mm per year).

2.11 SUMMARY

This review has explored the impacts of forestry on annual streamflows and flow regime, based on published case studies from the USA, South Africa, New Zealand and Australia. The studies reviewed spanned a variety of physical settings and covered a wide range of forestry activities. We conclude by listing the key generalisations which can be made from these case studies. These generalisations are qualitatively defined here as ‘well established’, ‘supported by limited evidence’ and ‘speculative’.

Well established

- Mean annual evapotranspiration (ET) is higher for forests than for grasslands; the Holmes and Sinclair (1986) relationship provides a guide to comparative mean annual ET rates of grasslands and eucalypt forests for varying mean annual rainfall isohyets in south-eastern Australia.
- In south-eastern Australia, mean annual ET is higher in pine plantations than in native eucalypt forests, primarily due to differences in rainfall interception.
- In South Africa, mean annual ET is higher in eucalypt plantations than in pine plantations, primarily due to differences in growth rate.
- Afforestation of grasslands results in reductions in mean annual streamflow, low flows and high flows.
- Forest clearance results in increases in mean annual streamflow, low flows and high flows; these increases are transient if the forest is permitted to regenerate.
- The degree of streamflow increases following forest logging is linearly proportional to the area of forest logged.
- In forests which are cleared but permitted to regenerate, streamflow increases usually peak in the first three years following treatment; streamflows normally return to pre-treatment levels between 4 and 10 years after disturbance, but may take as long as 25 years to recover.
- The streamflow impacts of forestry activities are amplified by increases in mean annual rainfall; absolute impacts are diminished in drier areas.

Supported by limited evidence

- Forest age affects ET rates, and thus streamflows, in moist eucalypt forests; old growth forests yield significantly more streamflow than regrowth forests of the same species, aged 20-30 years.
- In South Africa, plantation age affects ET rates, and thus streamflows, in pine plantations; streamflow reductions in *P. radiata* plantations tend to diminish after age 27 years.
- In South Africa, afforestation of grasslands reduces low flows relatively more than median and higher flows.
- Forest thinning has similar peak impacts on streamflows as forest clearance, provided that equivalent basal areas are affected; however, streamflow increases tend to persist longer for patch cuts than uniform thinning.

Speculative

- Forest age affects ET rates in dry eucalypt forest, though there is no hydrometric evidence to show that streamflows reduce to below pre-treatment levels.
- Transpiration per unit leaf area of forest declines as eucalypt forests age.

3. WATER QUALITY REVIEW

3.1 INTRODUCTORY REMARKS

This chapter restricts itself to the issue of ‘water quality’ and more specifically to our understanding of the potential impacts of logging, roading, and forest plantations on catchment water quality.

There are a number of preliminary definitions of scope required before we review the literature. The first pertains to the definition of ‘water quality’, which is most commonly assessed in terms of physio-chemical indices such as temperature, suspended sediment concentration, dissolved solids and nutrients. The appropriateness of these indices alone to provide an effective measure of 'water quality' have been debated over the past 5 years, with the result that a much broader definition is now commonly employed. Much emphasis has been placed on the need for additional ‘biological’ indicators to assess the entire stream ecosystem and not just the physio-chemical properties of the water. The National Water Quality Management Strategy (NWQMS) and the Monitoring River Health Program (MRH) were developed, in part, to address the disparity between definitions and definable parameters of water quality. The NWQMS aimed to provide a consistent national framework within which all stakeholders, from government agencies to local communities can contribute to better water quality management. It included a policy and principles document, and detailed sets of guidelines for maintaining and improving water quality. The MRH programs aims to develop a national approach to standards and guidelines and places considerable emphasis on biological and other indicators of water quality and river health. The debate about whether to use biological methods, chemical methods or a combination of both should centre on the objectives of the exercise. If biological impact is to be minimised, however, it must be accepted that whenever possible, biological indicators should be used (CSIRO, 1992). There are few studies in Australia that use a combined chemical-biological index of water quality so this review is necessarily biased towards studies that use sediment loads and turbidity as a reference for water quality standards.

The second aspect that requires clarification is the interpretation of literature findings with respect to judgements on the degree of impact. Some studies use terms such as ‘significant’, ‘slight’ or ‘not perceptible’ with respect to the observed impacts. Doeg and Koehn (1990) for example note "some increase in sediment accession to streams following logging, although some of these increases have been small". On the other hand, Cornish (1980, 1981, 1983, 1989a) concludes "in general, forestry operations do not have an adverse impact on stream turbidity levels" (Cornish, 1983). However, the reported values of turbidity in each of these data sets were actually higher in unlogged catchments than those that experienced some degree of logging, making this statement somewhat ambiguous. Quantifying changes in water quality and quantity, as significant, large or small is both subjective and highly dependent upon the accuracy of the measurement techniques employed. Interpretations of 'acceptable' changes to water quality may be quite different depending upon whether the catchment's water resources are for consumptive (eg. drinking water, irrigation and other commercial uses) or non-consumptive (eg. human recreation, maintenance of aquatic life) use. Similarly, the issue of water quantity is, understandably, of higher priority in catchments where rivers are used for water supply purposes. Consequently, while some studies describe the effects of timber production on water quality and quantity as "adverse" or "minimal", these are based on a fairly subjective idea of what is acceptable for a given water use. Schofield's (1996) simple tripartite classification is potentially more useful as a reference point defining the likely impacts of forest practices as;

- ***Low Impact***: small or transient activities with no observable effects (eg tree fall, small patch logging, and low intensity selective logging).
- ***Medium Impact***: transient activities with short to medium term effects but system recovery (eg intensive logging and regeneration, clearfelling and regeneration, slash and bun agriculture).
- ***High Impact***: permanent changes with long term effects (eg partial or complete conversion to agriculture, permanent forest thinning, intensive production forestry).

Where possible we interpret the literature findings within the context of this classification scheme so that the reader can have a qualitative measure of our interpretation of impact across the range of studies.

3.2 REPORT STRUCTURE

The potentially adverse impact of forestry activities on soil and water values has been recognised in many Federal and State Government reports (Cameron and Henderson, 1979; DWR, 1989; OCE, 1988; LCC, 1990; RAC, 1992). The Resource Assessment Commission of Australia (RAC, 1992) concluded, however, that there is scant quantitative data available on the relationship between timber harvesting activities and environmental parameters such as soil erosion, water quality, and biota. Doeg and Koehn (1990), and most recently, Dargavel *et al.*, (1995) have made detailed reviews of the literature. The latter provide a very comprehensive review of the issues surrounding 'logging and water' specifically for the south eastern seaboard of Australia. In particular, the review includes useful summaries of the major landuse regimes (eg logging, silvicultural and transport systems) and the current processes of regional assessment and public policy. Rather than duplicate these reviews, this report draws together key experimental and theoretical observations from previous studies and using these data to construct basic generalisations that are either 'well-supported' or 'speculative' with respect to the literature findings. This approach, used previously by Schofield (1996), allows a more realistic assessment of our ability to predict likely impacts for specific catchments or regions. This style of predictive management is now regarded as essential with increasing public awareness of the environmental issues surrounding timber harvesting, particularly native forests, and major land use impacts on water values. There is also a growing need for environmental agencies such as the EPA to construct a framework for the prescriptive and legislative management of timber harvesting practices.

3.3 WATER QUALITY AND TIMBER HARVESTING: TRADITIONAL APPROACHES TO THE ISSUE

Our current understanding of the impacts of forest harvesting practices on water quality stem largely from two research approaches which have been used to address this issue for over 30 years. The first approach centres on in-stream measurements of sediment concentrations and turbidity at the catchment outlet, usually using a paired-catchment approach monitored before and after the period of major disturbance. The second approach has centred on quantifying erosion rates on specific land elements such as roads, tracks and general harvesting areas (GHA) and using these data to construct sediment budgets and scaling approaches to assess changes in catchment water quality due to forest harvest disturbances.

3.3.1 Problems with these approaches

Both approaches have inherent problems, many of which are commonly overlooked in our interpretation of the research findings. The former catchment monitoring approach is commonly referred to as a ‘black-box’ (Walling, 1983) where data at the outlet is interpreted without any understanding of the relative contribution of sediment sources throughout the catchment. The main problem with this approach is the difficulty of ‘finger-printing’ the sediment, and determining whether the material measured at the outlet is in fact derived from forest harvesting activities, or the remobilisation of secondary sources and/or in-channel deposits. Increased turbidity at the catchment outlet may be related to increased channel erosion due to changes in the streams hydrograph and storm flow response after harvesting, and may not necessarily relate to increased hillslope erosion or delivery rates. The problems are particularly complex in mixed land use catchments where it is almost impossible to differentiate the relative contribution of material from the range of sediment sources. There is also the secondary problem of the accuracy of the suspended sediment data due to problems with event sampling, technical equipment failures and matching the rainfall record in the pre-logged and post-logging measurement periods. Bren (1990) suggests that both Australian and overseas catchment turbidity studies do not provide a clearly transferable message on sediment loads and forestry operations. This is reflected in the study of Olive and Rieger (1987) where an analysis of suspended sediment response patterns in small streams around Eden, NSW, showed "marked variability".

Doeg and Koehn (1990) also draw attention to the accuracy and reliability of reported values of suspended solids and turbidity in the literature. They suggest that poor sampling frequency means that suspended sediment peaks and total loads have probably been underestimated, bed-load levels have not been investigated, and deposited sediments have been ignored. Within the Australian context, the length of time over which studies need to be conducted in order to assess the effects of forestry operations on water quality is further cause for concern. Some overseas studies have shown that elevated levels of stream sediment and woody debris were still present 20 and 50 years after logging (Beschta, 1978; Webster *et al.*, 1987; Andrus *et al.*, 1988; Platts *et al.*, 1989). Only one Australian experimental catchment has been studied for more than 30 years (MMBW, Coranderrk Experiments) with the majority investigated for periods of less than 15 years (Doeg and Koehn, 1990). Overall, short-term catchment monitoring studies are of limited value in understanding the magnitude of the disturbance or in pinpointing best options for remedial or preventative practices within the catchment.

The problems with the second, on-site erosion approach stems largely from the scale of analysis. Not all of the sediment eroded from a particular hillslope will be delivered to the stream. Many plots are too small to measure or quantify redistribution and storage processes. Quantifying this delivery ratio remains difficult because of the spatial and temporal variability in some of the controlling factors such as hillslope shape, soil type, vegetation, rainfall intensity and the degree of disturbance.

There have been recent advances, however, in the application of both approaches. The former has benefited considerably from the introduction of conservative sediment tracers to finger print the sources of sediment within a catchment and construct a sediment budget using tracer data. The second approach has been advanced by larger plot-scale studies where the physical processes of sediment storage and redistribution have been quantified, allowing a more accurate assessment of delivery rates and ultimately hillslope contributions. More importantly, recent advances in our understanding of sediment and water quality have led to the recognition of the data that are essential to fully understand the issue of forest management impacts on water quality.

3.3.2 Fundamental Data

In order to fully understand and quantify the impacts of forest practices on water quality we require a fundamental understanding of:

- The nature of sediment sources and their spatial distribution with respect to streams.

  Justification: not all parts of the disturbed forest generate sediment equally: it is essential therefore, to quantify the relative contributions from a range of sources and map their location with respect to streams.

- The nature of the delivery pattern from source to stream and potential for storage both on the hillslope, in erosion control structures and in near-stream areas.

  Justification: not all sediment eroded from a particular source will be delivered to the stream or catchment outlet. It is important to understand the nature of the delivery and storage patterns and determine the most potentially damaging delivery pathways with respect to in-stream water quality.

- The effectiveness of best management practices with respect to sediment production and delivery.

  Justification: the potential impact of forest harvesting practices on water quality may be reduced and transient if best management practices are employed and proven to be successful.

Data on these three key variables allow us to construct a more meaningful and accurate assessment of any likely impacts. The problem lies in acquiring data for a given region or catchment. Few studies in the literature address all of these issues. Taken as a whole, the studies are conducted in a range of forest environments of varying topographic and soil characteristics and predictive management relies heavily upon extrapolation of data from different scales and regions and the use of models to predict likely impacts. The following section reviews our understanding of these key variables and is followed by a review of some approaches to predictive management. The review concludes by identifying knowledge gaps and issues of immediate concern for present and future management of forested catchments.

3.4 SEDIMENT AND NUTRIENT SOURCES

3.4.1 Sediment Sources

Many studies describe the effects of particular land uses on sediment yields without differentiating between sediment sources. Of all forestry operations, however, the literature both in Australia and overseas, points consistently to road infrastructure as the most damaging effect on sediment accession to streams. Langford and O'Shaughnessy (1980) note that the prime source of sediment accession in their experimental coupes was roads and tracks. Langford *et al.*, (1982) argue that the "small" increase in sediment concentrations in the Coranderrk catchments were due to "poor stream crossings" rather than direct logging activities *per se*. Kreik and O'Shaughnessy (1975) also detected the effects of pre-logging road construction on suspended solids and turbidity. Davies and Nelson (1993), investigating the impacts of sediment accession on fish and macro invertebrates, suggested that "sediment input from uncontrolled road crossings is considerable". These roads, draining 6% of the catchment, were constructed some 30-50 years prior to the study but remain active sources of sediment through recreation use.

Reid and Dunne (1984) also found that the major source of sediment on logging roads was the pounding of the surface by heavy log trucks but once traffic stopped, unsealed forest roads stabilised and sediment loss from the road surface "greatly diminished". Sediment yields from logging roads have been well-documented in studies from the US, and in general, show a 2- to 50-fold increase over background levels (Reid, 1993). Sediment yields decrease rapidly after road use is discontinued and logged areas regenerate so yields measured more than 5 years after logging are usually less than five times than background rates (Reid, 1993).

Recent field experiments in selected forest management areas in southeastern Australia also highlighted the importance of temporary roads or forest snig tracks as important sources of surface sediment (Croke *et al.*, 1997). Snig tracks in the highly erodible granite soils around Bombala, NSW, yielded sediment erosion rates of the order of 12 t/ha of track surface for a 100 y storm of 30-minute duration. These yields were almost a magnitude lower than those reported for more stable soils on the Ordovician soil types around the coastal forests near Bermagui where sediment transport processes were predominantly sheet flow (Croke *et al.*, 1997; Croke *et al.*, in press). Wilson (in press) also reports similar erosion rates on forest snig tracks on highly erodible sandy soils in Tasmania. Radionuclide tracers also confirmed snig tracks as net erosion areas with estimated yields in the order of 70 t/ha per year (Wallbrink *et al.*, 1997). Similar experiments on a range of secondary access and log access tracks in Bermagui on Ordovician Metasediment soils produced yields of ~ 8t/ha for a 100 y storm of 30-minute duration on a stretch of forest road. The road is well used by heavy logging trucks and private access vehicles (Croke *et al.*, unpublished data; Appendix 1).

Unsealed forest roads can represent between 1-5% of a managed forest, with tracks and temporary roads occupying larger areas between 5-10% of the catchment or logging compartment. In the eucalypt forests of southeastern Australia, for example, Mathews and Croke (1998) estimated that temporary roads and tracks formed 12-15 % of the 160 ha forest compartment. In plantation forests, the density of roading is considerably greater and the effects of this have been reflected in the magnitude of sediment production reported in some studies. Increased streamwater suspended sediment and turbidity have been associated in particular with the establishment and management of *P. radiata* plantations (Cornish, 1989b). Factors responsible for this include a high roading density, the frequent occurrence of streamside roading networks and a reliance on downhill snigging (Cornish, 1989b).

Grayson *et al.*, (1993) attempted to separate the effects of road use and maintenance on water quality from logging operations. They found that annual sediment production from forest roads was in the range of 50-90 tonnes of sediment per hectare of road surface per year. The use of gravel and increasing the level of road maintenance reduced sediment production. Conversely, when road maintenance was not increased, sediment production increased by approximately 40%. In discussing sediment generation on forest roads, Haydon *et al.* (1991) showed that unsealed forest roading for recreation can increase sediment generation by two orders of magnitude over undisturbed catchments (increasing from 0.3t/ha/yr to 30t/ha/yr). The intensity and duration of road use and the level of road maintenance influenced these effects. Numerous strategies have been developed to limit sediment production from forest roads and tracks, including revegetation, gravelling and regular maintenance (Haupt, 1959; Diseker and Richardson, 1962; Kidd, 1963; Dryness, 1970, 1975; Carr and Bullard, 1980; Cook and King, 1983; Burroughs *et al.*, 1984; Kochenderfer and Helvey, 1987; Burroughs and King, 1989; Heede and King, 1990).

In contrast to the wealth of studies, mainly from the United States of America, reporting sediment production rates from forest roads, there are relatively few studies that compare the magnitude of sediment generation from a range of sources. Sediment production rates from forest snig tracks were compared with those from the general harvesting area for 13 sites in the Eden and East Gippsland Forest Management Areas (Croke *et al.*, 1997). Field experiments revealed that sediment and runoff production on the GHA were several orders of magnitude lower than the snig tracks or forest roads (Croke *et al.*, 1997; Croke *et al.*, in press). Although partially disturbed during harvesting, the retention of a high degree of forest vegetation contributes to the lack of sediment transport in these areas. Channelised flow is rarely present on the GHA limiting the ability of runoff to transport large amounts of sediment. Runoff production appears to be dominated by the bare or more disturbed areas, however, suggesting that if severe broad-scale disturbance occurred, sediment transport rates and soil losses on these areas would be significantly increased (Croke *et al.*, 1997). Values of sediment movement reported in this study, which utilised large rainfall simulators, appear consistent with erosion rates reported for disturbed forests elsewhere (Dissmeyer and Stump, 1978; Ziegler and Giambelluca, 1997; Wilson, in press). It should be noted, however, that sediment yield estimates are more commonly reported in terms of annual averages, as compared with the event base values produced using the simulator studies.

The persistence of roads and tracks as significant source strength has also been investigated in a number of studies (Megahan, 1974; Beschta, 1978; Megahan *et al.*, 1983). The rainfall simulator experiments in the Eden and East Gippsland FMA (Croke *et al.*, 1997) were conducted on snig tracks of varying age since logging. The results indicated that there is a temporal recovery both in terms of runoff and sediment production over a period of 5 years after logging where sediment production levels had declined on the snig tracks to levels comparable to a lightly disturbed GHA (Croke *et al.*, 1997). The discontinued use of tracks between cutting cycles is seen as a significant factor in limiting sediment supply for transport. Similar periods of recovery have been reported on highly erodible forest roads (Megahan, 1974). Recovery was also observed on the GHA over this time frame of 5 years, though the degree of recovery was lesser, as the potential changes in soil and vegetation properties was much lesser. On roads the intensity of traffic-usage is also seen as a key factor in the persistence of these areas as a sediment source. Roads that are used infrequently but remain open to the public for recreation had generation rates almost one order of magnitude lower than those sections of road used frequently by both logging trucks and private traffic (Croke *et al.*, unpublished data).

Compaction of the surface soil is commonly noted to be a persistent feature of soil disturbance during logging with some studies reporting that impacts persist for up to 30-50 years after logging (Greacen and Sands, 1980; Increate *et al.*, 1987). In terms of sediment production, however, recovery times appear to be significantly shorter of the order of 5 years (Megahan, 1974; Reid, 1993; Croke *et al.*, 1997). Factors that are likely to affect the rate of recovery are soil type, regeneration rates and the persistence of rills or gullies. Once formed rills and gullies are difficult to remediate and represent the continued persistence of concentrated flow paths over time.

3.4.2 Comparisons with other landuses

Patric *et al.*, (1984) contrasted sediment yields from forested watersheds (<5 km2) to sediment yields from watersheds with other landuses (primarily agriculture). In the eastern U.S. the average annual sediment yield for managed and unmanaged forested watersheds was about 0.15 Mg/ha as compared to 0.35 Mg/ha for the other watersheds. In the western, forested watersheds had a mean sediment yield of 0.15 Mg ha-1 yr-1 as compared to 0.42 Mg ha-1 yr-1 for other land uses. Patric *et al.*, (1984) also compared the concentrations of suspended sediment in major rivers draining mostly forested areas with rivers draining areas with other landuses. The concentration of suspended sediment was about 10 times greater in rivers draining non-forested areas. Yoho (1980) compiled erosion rates for a variety of land uses on small watersheds in the south of the USA. Intact pine forests yielded the lowest quantities of sediment (from 0 to 0.2 Mg ha-1 yr-1), with carefully clearcut forests (applying BMP's) yielding only moderately more (0.1 to 0.4 Mg ha-1 yr-1) over one to several years. Pastures produced 0.9-4.5 Mg ha-1 yr-1, and carefully cultivated agricultural fields were found to yield from 0.9 to 16.8 Mg ha-1 yr-1. Harvesting and site preparation without use of BMP's yielded between 3 and 14 Mg ha-1 yr-1 for one to several years, temporally matching the erosion rate from carefully cultivated fields.

3.4.3 Broad Generalisations

Well Established

- Unsealed forest roads are the major sources of sediment in managed forests.
- Road usage is a critical factor in explaining sediment production rates on roads.
- Sediment yields from forested (managed and un-managed) watersheds are considerably lower than those from other landuses, particularly agriculture.
- Sediment production rates on roads and tracks decline within the time frame of 2- to 5 years.

Limited Evidence:

- The GHA is not a significant source of sediment due to limited sediment availability, high retention of vegetation cover and spatially variable infiltration rates.

Speculative:

- Hillslope disturbances during logging result in significant post-logging changes in stream turbidity at the catchment outlet.

3.5 NUTRIENT SOURCES

A detailed review of nutrient production and potential losses due to such factors as fire soil disturbance and erosion is presented in Attiwill and Leeper (1987). In general terms, nutrients in the forest ecosystem are contained within the living biomass of plant and animal life, within dead organic matter and the soil, and are cycled through this soil-plant-litter subsystem. Inputs to the nutrient pool come from weathering of the soil parent material or from the atmosphere. Atmospheric inputs include fixation of atmospheric gases (eg nitrogen fixation), aerosols (particles suspended on air) or in rain or other precipitation. Inputs from parent material can be considered to be very slow. The two most dominant macronutrients in our soils are nitrogen and phosphorous. Most of the nitrogen in surface soils is associated with organic matter. The amount of nitrogen in the form of soluble ammonium and nitrate compounds is seldom more than 1-2% of the total present, except where large applications of inorganic fertilisers have been made. Organic nitrogen is largely protected from loss but largely unavailable to higher plants. This process of tying up nitrogen in organic forms is called immobilisation; its slow release, specifically organic to inorganic conversion, is called mineralisation. Only a small proportion of total soil N (<5%) is readily mineralisable, and this is recycled through litter decomposition with turn over rates of between 3-5 years (Attiwill and Leeper, 1987). However a much larger proportion of total soil N, with slow turn over rates, is available for plant uptake over several rotations. These long tern reserves of N are estimated at 40% of total soil N (Hopmans *et al.*, 1993). Inorganic nitrogen is most susceptible to loss from soils by leaching and volitization. Phosphorous is also mostly present in organic forms in forest soils (Kelly and Turner, 1978) or is temporally converted to organic forms in the early stages of litter decomposition by microbial activity (Harrison, 1988). There are two important pathways for the export of nutrients from areas of forestry operations: the solution pathway is where nutrients moved dissolved in water often dominantly by sub-surface water flow, and the sorbed pathway is where nutrients are attached to sediment. This second pathway becomes significant where soil erosion is present.

The main factor affecting nutrient depletion is the overall distribution of nutrients within the soil profile. Soils with large reserves of nutrients held in lower layers (eg basaltic soils) are much less susceptible to nutrient depletion than soils with poor reserves of subsoil nutrients (eg soils formed on quartzite) (Turner and Lambert, 1986). With forest ecosystems highly dependent upon litter fall processes, it is not surprising that most available nutrients are concentrated on the soil surface and can be directly related to measures of organic matter content.

Following the site exposure that accompanies logging, some forest soils experience an accelerated release of certain ions into the solution pathway from the mineralisation of organic matter and from mineral weathering (Aubertin and Patric, 1974). The extent to which those ions released by exposure are removed from the site by leaching to streams is a function of the uptake of those ions by vegetation and the ion exchange properties of the soil. A number of studies have observed increased leaching of dissolved nutrients from logging slash (Likens *et al.*, 1970; Hewlett *et al.*, 1984; Meyer and Tate, 1983). Hopmans *et al.*, (1987) found that export of nutrients and suspended solids were significantly higher because of increased discharge following clearing as a consequence of increased water exported from the catchment. The impact of harvesting practices on nutrient losses have focussed primarily on the relationship with prescribed fires and regeneration burns. Increased concentrations of nutrients in streams draining logged catchments subject to prescribed fires are primarily the result of direct precipitation of ash into the stream (Spencer and Hauer, 1991); overland flow that has been in contact with ash (Grier and Cole, 1971); and nutrient transport from groundwaters after leaching (Grier and Cole, 1971).

There are few studies that investigate the level of nutrient losses associated specifically with surface erosion by overland flow. Croke *et al.*, (1997) examined representative concentrations of total nitrogen (TN) and phosphorous (TP), and their associated forms such as nitrite (N02), nitrate (N03) and ammonia (NH4) and reactive (P04 2) and dissolved phosphorous, transported via overland flow from the nine disturbed sites of vary age and soil type. Nutrient concentrations on the sites were relatively low with mean concentrations in the order of 2.7 mg/L and 0.42 mg/L for TN and TP respectively. Nutrient loads varied according to the degree of site disturbance and were significantly higher on the snig track elements compared to the GHA. Net export of TN from the plots averaged about 75, 32 and 9 mg/m2 for sites of varying age (0, 1 and 5yrs post burning) using a series of rainfall simulator events as described in Croke *et al.*, (1997). This value represents total nitrogen loads leaving a 300 m 2 hillslope plot and reflects the effects of redistribution and storage processes over this area.

Forest fertilisation is commonly regarded as a significant factor in explaining increased nutrient concentrations in streams draining managed forests. Most studies in the USA have shown that these increases are too small to degrade water quality (Binkley and Brown, 1993). A few exceptional cases have been reported where nitrate concentrations in excess of 10 mg-N/L were recorded several months after careful application of fertilisers in the Fernow Experimental Forest in West Virginia (Kochenderfer and Aubertin, 1975; Helvey *et al.*, 1989, Edwards, 1991). Fertilisation is a routine practice on many intensively managed pine forests in the Southeast of the United States of America but few studies have examined fertilisation effects on water quality (Shepard, 1994). In the pacific North West several dozen forest fertilisation studies (Fredriksen *et al.*, 1975; Meehan *et al.*, 1975, Tiedemann *et al.*, 1978, Bison 1982, 1988, Hetherington, 1985, Bisson *et al.*, 1992a) found nitrate concentrations well below the drinking water standard. A few harvesting studies have shown slight increases in phosphate concentrations after logging (e.g. Salminen and Beschta, 1991) but these increases were far too small to degrade water quality, “although some increase in stream productivity may have resulted”. This appears to summarise the potential effects of increased nutrients on fish populations and the literature in the US contains no examples of damage to fish populations from nutrient concentrations following harvesting or fertilisation. The effects of fertiliser application in Australian pine plantations have not been reported. Recent work initiated in the Croppers Creek catchment in Victoria aim to address this issue although not quantitative data has emerged from the project to date.

Some mention to the difficulties of measuring nutrient concentrations in water draining forested catchments has also been made. The measurement of dissolved solids and nutrients may be plagued with similar problems to the measurement of sediment concentrations, particularly with regard to the relationship between concentration and discharge. A water-sampling program intended to investigate suspended sediment or nutrient loads and based on regular monthly or weekly samples may be ineffective in detecting changes in nutrient concentration and load due to forestry operations. (Hart, 1982; Campbell, 1982, 1986). In addition, there is a growing awareness that the traditional total phosphorus and soluble reactive phosphorus parameters incorrectly characterise nutrient flux in streams and as such, are poor estimators of bio available phosphorus in flowing water systems (Hart, 1982).

3.5.1 Comparisons with other landuses

Omernik (1977) estimated the concentrations of total N and P in streams draining large areas of differing land use. Streams draining forested areas had concentrations on N (0.6 mg/L) and P (0.02 mg/L) that were an order of magnitude lower than streams draining agricultural areas (5.4 mg N/L and 0.2 mg P/L). Nitrate-N was also lowest in streams draining forests. A summary of water quality from the USGS’s Hydrologic Bench Mark Streams showed that “natural” watersheds (primarily managed and unmanaged forest) averaged 0.06 mg N03-N/L compared with 0.3 mg-N03-N/L for other streams (Biesecker and Leifeste, 1975). Most forest harvesting studies in the United States have documented increased concentrations of nitrate following harvesting (Binkley and Brown, 1993), but in almost all cases these increases have remained well below the 10 mg-N/L drinking water standard. Two notable exceptions include the high concentrations (average 5 mg-N/L) of nitrate observed in waters draining from high elevation forests in the Southern Appalachian Mountains (Silsbee and Larson, 1982). Factors contributing to elevated nitrate concentrations may include high rates of atmospheric nitrogen deposition and low rates of nitrogen uptake by the forest which may be affected by harvesting and by changes in the vigour that have been attributed to stand maturation or regional air pollution.

3.5.2 Broad Generalisations

Well Established

- Nutrient concentrations in streams draining forested catchments are considerably lower than those reported for other landuses, primarily agriculture.
- The dominant cause of increased nutrients in streams if observed, is due to the effects of prescribed burning and wildfire.
- Observed impacts are short-lived and transient with no long-term effect.

Limited Evidence

- Fertiliser applications cause no increase in nutrient concentrations of streams draining managed forests.
- Fertiliser applications have no impacts on other values such as stream productivity, fish populations.

Speculative

- Timber harvesting activities significantly affect nutrient concentrations measured using a discharge–concentration relationship at the catchment outlet.

3.6 SEDIMENT DELIVERY PATTERNS AND POTENTIAL FOR STORAGE

Once sediment is generated, the portion of sediment delivered to the stream is the key variable that is influenced by both environmental attributes and management inputs. Although surface erosion rates are widely measured, much less is known of sediment delivery rates to channel networks. A common perception is that all sediment that is eroded is delivered to the stream. Many predictive approaches have combined empirically-derived or plot erosion rates with arbitrary sediment delivery ratios, resulting in over-predictions of likely in-stream responses.

Forestry environments are relatively unique in their ability to store sediment due to the retention of a relatively high percentage of vegetation. Even in a disturbed state there is a high degree of material such as trash, litter, stones and fallen logs that remain on the ground surface providing a cover for both the removal of soil particles from the exposed soil and their delivery downslope. This fact has been formally recognised by the inclusion of a cover-management factor in the Universal Soil Loss Equation (USLE) as applied in forestry environments

(Dissmeyer and Foster, 1980). Williams (1975) also incorporated a sediment delivery term into the USLE and Tollner *et al.*, (1976) developed an equation for estimating deposition from sheet flow as a function of flow character, vegetation character and transport distance through vegetation. Heede *et al.*, (1988) examined the role of vegetation recovery after a chaparral fire in controlling the timing and rates of sediment delivery to streams and thus, in controlling the timing and location of channel adjustments.

Each sediment source is likely to have its own very specific delivery pattern dependent upon its spatial distribution within the catchment and the management practices employed. Forest roads for example have a very specific delivery pattern determined by the arrangement and location of drainage structures such as culverts and mitre drains within the catchment. Runoff from road surfaces is commonly discharged at concentrated outlets onto the adjacent hillslope via a network of culverts or drains. In contrast, drainage of temporary roads or forest snig tracks is a more dispersive pattern resulting in the redistribution of runoff and sediment via a network of cross drains. A number of studies have now illustrated the potential significance of concentrated paths at road outlets with respect to channel initiation and severe gullying. Montgommery (1994) for example estimated that gullying along ridge-top roads in a catchment in Oregon resulted in a 23% increase in the natural drainage density. Wemple *et al.*, (1996) also observed a significant increase in the natural drainage density due to road construction.

Gully initiation at road outlets has also been recorded in the Cuttagee Creek catchment around Bermagui in the south eastern part of NSW (Mockler and Croke, in prep.). In this study, gully initiation resulted in a 6% increase in the natural drainage density of the catchment over a period of approximately 30 years. The study also indicated that the contributing area to the drain outlet along with the slope of the hillslope at the discharge point were significant factors in explaining gullied pathways. The threshold relationship identified between these two variables provides a robust method of preventing gully initiation at road outlets. The study also recognised a clear relationship between gully initiation and the type of drainage structure used eg mitre drain or culvert with most gullying associated with culvert pipes on steep hillsides. Road culverts have a restricted use in forest roads in that they are only used where and when other drainage structures can not be used- that is to drain a road cut into the hillside. Significant gully initiation was also observed to result from soil disturbance during pine (*Pinus Radiata*) plantation harvesting in Bombala where the placement of wind-rows was also recognised to concentrate runoff into certain parts of the landscape increasing the likelihood of channel initiation and gullying (Prosser and Soufi, in press). Channelised flow paths form a very efficient conduit for the delivery of sediment and nutrient to streams- once gullies are formed they are also very difficult to remediate so prevention is the best option.

Davies and Nelson (1993) recently illustrated that fine sediment input to these ephemeral, first order streams, such as those formed due to gullying at road outlets, is significantly enhanced by logging on steep slopes, by factors of two to three times the median values for unlogged streams. These small ephemeral streams are often treated in much the same way as the rest of the coupe, but have a more significant role in the export of fine sediment to downstream sites (Davies and Nelson, 1993). Recent changes to the Victorian Code of Practices and the Pollution Control Licence in NSW have afforded these areas greater protection with respect to sediment delivery. The steeper slopes and potentially larger contributing areas of first order streams means that they play a significant role in the delivery of sediment and nutrient downstream. Duncan *et al.*, (1987) for example found that over 50% of the fine-grained material delivered to steep first order streams reached sites downstream. This summarises the relationship between the size of the transported material and the delivery ratio. Many studies report an inverse relationship between the percent delivered and the size of entrained sediment, reflecting processes of preferential erosion and deposition at various spatial and temporal scales throughout the catchment (Walling, 1983). Croke *et al.*, (1997) also report a relationship between the size of the eroded material and sediment delivery at cross banks draining forest snig tracks in southeastern NSW. Similar conclusions have been identified in a series of rainfall simulator field experiments on the effectiveness of riparian buffer strips in trapping sediment of varying size (Pearce *et al.*, 1998).

The ability of the hillslope to absorb sediment and runoff and thereby control sediment movement downslope is dependent upon the specific topographic, soil and vegetation characteristics of the hillslope. Hillslopes that are disturbed during harvesting may represent an additional sediment source, potentially limiting the ability of the area to store sediment. Much of the recent literature regarding sediment delivery from hillslopes centres around the effectiveness of the riparian or buffer vegetation in trapping sediment prior to entering the stream and this is discussed in more detail in the following sections.

Sediment delivery in large watersheds has also been correlated with morphological factors. Roehl (1962) for example found that the proportion of sediment eroded on the hillslopes that arrives at a watersheds mouth decreases with increasing watershed area and channel length, and increases with increasing relief ratio. This relation implies that some sediment is lost in transport and may reflect lowland aggradation or chemical dissolution during transport and storage. Khanbilvardi and Rogowski (1984) and Novotny and Chesters (1989) reviewed methods of estimating delivery ratios on the scale of plots and hillslopes.

3.6.1 Broad Generalisations

Well Established

- Channelised pathways forming at road drainage outlets form the most efficient conduit for sediment and nutrients.
- Sediment delivery ratios are closely associated with the size composition of the in-situ and eroded soil.

Limited Evidence

- The interaction between factors such as slope, runoff, and morphological factors in determining sediment delivery ratios for both the hillslope and catchment.

Speculative

- Data sets constructed from empirical relationships or plot erosion data that do not accommodate for processes of deposition and storage within a land element. These data are likely to over estimate the hillslope contribution and consequently the magnitude of catchment response

3.7 EFFECTIVENESS OF BEST MANAGEMENT PRACTICES IN PROTECTING WATER QUALITY

Several methods are used in forestry operations to mitigate the impact of logging on streams. These include the use of riparian buffer strips of varying widths, patch harvesting, siting and design of roads and road crossings to minimise sediment inputs, and restrictions to logging activities in relation to coupe slope and soil type. There are a number of studies in the literature which investigate the effect of some or all of these prescriptions in protecting soil and water values. An early, but relevant, example of this type of study is that of Hornbeck and Reinhart (1964), who examined the effects of prescriptive measures (eg bars across snig tracks, a ban on stream crossing and the location of roads away from streams) on sediment concentration in the United States. Suspended concentration varied from 56,000 mg/L where no prescriptions were employed to 15 mg/L when all of the above were imposed. Lynch *et al.*, (1975, 1985) also report the effectiveness of BMP's in minimising impacts on sediment concentrations in Pennsylvania where only half of the watershed was harvested, 30-m buffer strips were retained along streams, the locations of roads and tracks were determined in advance and all roads and trails were rehabilitated after logging. Sediment concentrations in the first year after harvest averaged 1.7 mg/L for the control watershed and 5.9 mg/L for the harvested. Sediment concentrations remained slightly elevated above the control watershed for about 10 years and the researchers concluded that while the implementation of BMP's did not completely prevent impacts, the impacts were relatively small and of no direct concern to water quality standards (Lynch *et al.*, 1975; 1985).

Grayson *et al.* (1993) found that applying a strict enforcement of Code prescriptions (eg suspension of logging during wet weather, protection of runoff producing areas with buffer strips, and the management of runoff from roads, snig tracks and log landings) eliminated intrusion of contaminated runoff into the streams, thereby avoiding the adverse effects of logging. Karr and Schlosser, (1978) also illustrated that while unmitigated clearcutting over a period of years doubled suspended sediment concentrations in runoff and increased nitrate levels by a factor of four, clearcutting with the retention of buffer strips caused only a 50% increase in suspended sediments and had no effect on nitrate levels.

Recent field experiments on snig tracks in the Eden and East Gippsland Forest Management Areas also highlighted the importance of track rehabilitation and drainage after logging. The field experiments suggested that around 50-60% of eroded material is stored in cross banks draining forest snig tracks. The deposition rate was inversely related to the percentage fine material eroded from the snig track highlighting the relative ineffectiveness of these features in trapping fine material (Croke *et al.*, 1997; Croke *et al.*, in review). Given our concern with fine-grained material and their ability to transport adsorbed nutrients, great care should be taken to avoid exposing highly dispersive clay subsoils during cross bank construction. The predominant purpose of these features is to reduce the local catchment area so that the discharge plume at the outlet of the cross bank is minimised. Croke *et al.*, (in press) also reported that the practice of redistributing runoff at cross bank outlets after logging was a successful method of reducing the potential contribution of water and sediment to streams, particularly during small to medium rainfall events (2-10 years recurrence intervals). During the more extreme events of a 100 y storm, both the hillslope and snig track are generating runoff and the ability of the hillslope to absorb excess runoff is reduced. The spacing of cross banks becomes critical under these conditions, where the length of the discharge plume must not exceed the designated cross bank spacing. Field surveys on forest roads also highlight the importance of adequate drainage and drain installation (Mockler and Croke, in prep). Smith and O'Shaughnessy (1998) also report the effectiveness of obstacles or flow divergence structures at road drainage outlets in significantly reducing sediment delivery to streams.

Because of the importance of buffer strips as a prescriptive measure in stream protection, the following section provides a more detailed review of the literature relating to their role, width and placement in forest management strategies.

3.7.1 Buffer-Strips

The use of vegetated buffer strips as a method of controlling sediment accession to streams has been recognised and accepted in Australian forest operations for more than two decades. Vegetation in these buffer zones generally comprises that existing prior to logging operations and is retained with the objective of protecting drainage lines and streams. Clinnick (1985) reviewed 'Buffer strip management in forest operations', paying particular attention to their effectiveness as a physical barrier to the transport of displaced soil from roads and forest harvesting areas. Vol Norris's (1993) review of buffer strips placed greater emphasis on their potential for removing pollutants from surface runoff in both forested and agricultural environments. The most recent review of buffer strip management in controlling waterway pollution has been undertaken by Barling and Moore (1994) as part of the Land and Water Resources Research and Development Corporation's program initiative for the study of riparian lands.

The effectiveness of buffer strips in protecting water quality is outlined in the case-study results of Karr and Schlosser (1978), Lynch *et al.* (1985), Aubertin and Patric (1974); Martin and Pierce (1980) and Borg *et al.* (1988). Further examples are provided, mostly from overseas work, in the reviews of Clinnick (1985), Vol Norris (1993) and Barling and Moore (1994). Cornish (1989b) suggests, however, that there are numerous problems with the provision of streamside buffer strips in *P. radiata* plantations including the problems of wind throw in the later years of the rotation and management problems on what type of vegetation to encourage in the strip in the second rotation. In addition, it is not always possible to protect buffer strips from being burnt in these plantations where fire is commonly used as a tool in the establishment and re-establishment of *P. radiata*.

There is still considerable confusion and ambiguity regarding both the placement and width of buffer strips in catchments. For forested systems, there are two possible approaches for locating buffer strips; one based on determining appropriate sediment transport distances through the buffer strip and the other that attempts to protect runoff-generating areas in the landscape. In the case of the former, a 30 m buffer is typically regarded as effective in trapping most of the sediment from cleared areas, although absolute width is dependent upon specific site conditions (Clinnick, 1985; Barling and Moore, 1994). All the available literature on adequate buffer strip widths are, nonetheless, site-specific (Trimble and Sartz, 1957; Packer, 1967; van Groenewoud, 1977; Corbett *et al.* 1978; Cameron and Henderson, 1979; Chalmers, 1979; Graynoth, 1979; Bren and Turner, 1980; Borg *et al.* 1988). There is little or no data, which can be used to predict acceptable buffer widths under variable catchment characteristics. In one of the few Australian studies that examined the question of buffer widths, Borg *et al.* (1988) found that halving the buffer strip widths from 200 m to 100 m and from 100 m to 50 m had little if any detrimental effect on water quality. Their complete removal, however, led to changes in the stream channel profile and to algal blooms. In a recent study, Davies and Nelson (1994) examined the impacts of forest logging on in-stream habitat, fish and macro invertebrate populations in Tasmania and related the observed impacts to the width of the riparian buffer strip at each site. Their results are among the first in Australia to quantify changes in water quality due to altered buffer strip widths. Their conclusions state clearly that *"all impacts of logging were significant only at buffer widths of less than 30 m"*.

In an attempt to construct a more formal method of determining extensions to the minimum streamside reserve width, Doeg and Koehn (1994) formulated a 'Decision Support System' to determine buffer width extensions at the coupe level. This system requires the user to input certain data related to the physical characteristics of the forest coupe to be harvested and is designed for simple computerisation. Unfortunately, this system of checks and questions suffers from a lack of scientific data to validate the recommended extensions and is clearly too detailed to be included directly into a Code of forest practices or pollution control licence. Herron and Hairsine (1998) also examined a scheme for evaluating the effectiveness of riparian zones in reducing overland flow to streams and suggested that a riparian zone width not exceeding 20% of the hillslope length is a practical management option. They also concluded that buffer zones need to be distributed around the stream network where upslope sediment sources exist, if riparian buffers of realistic widths are to be effective. Some states, such as New South Wales, have constructed ‘windows’ outlining a range of buffer widths for varying soil, slope and erodibility classes.

In relation to protection based on runoff generating area, Cameron and Henderson (1979) recommended that buffer strips be required where the catchment area exceeds 100 ha and should extend along the entire length of the stream. In general, it is agreed that buffer strips should extend to the springhead or runoff confluence point of any sub-catchment and should be well upstream of any existing channel or streambed, since flow will occur at a higher point in the catchment once the forest has been cleared (Bren and Turner, 1980; O’Loughlin *et al.*, 1989; Finlayson and Wong, 1982). The factors that affect the location of variable source areas of runoff generation include: soil characteristics; topography; vegetation and weather (Moore *et al.*, 1991). Saturated source areas exist whenever the accumulated drainage flux from upslope exceeds the product of the soil transmissivity and the local slope (O'Loughlin, 1981). It is crucial when defining buffer strips in the field that all sources of runoff generation are included within the buffer strip zone. It is essential to incorporate the ‘saturated zone’, which is the area along the stream or drainage line that is permanently saturated (eg swampy ground) or becomes saturated (eg seepage area) with the onset of rain (O’Loughlin, 1981). Likewise, for buffer strips to provide protection during peak flow situations, Cornish (1975) proposed that catchment area, not stream permanence, be used as the criterion for defining the provision of buffer strips.

A number of equations have been formulated to determine where this condition applies in complex landscapes (Beven and Kirkby, 1977, 1979; O'Loughlin 1986; O'Loughlin *et al.*, 1989; Moore *et al.*, 1993). That of Moore *et al.*, (1993), that is essentially a refinement of previous equations, is designed to account for spatially variable evapotranspiration, deep drainage and vegetation characteristics. There are no empirical studies that have applied these equations to examining the impact of forestry operations on water quality.

3.7.2 Broad Generalisations

Well Established

- BMP’s play a significant role in the reduction of adverse effects in forested catchments.
- Forest buffer strips are an effective measure in reducing the volume of surface water and sediment/nutrients delivered to a stream.

Limited Evidence

- The best location and design of buffer strips in forested catchments of varying topography and landuse.
- The specific role and effectiveness of BMP’s on the hillslope versus those in the near-stream area.

3.8 PREDICTIVE MANAGEMENT

Many forest managers and environmental protection agencies now perceive the need for a quantitative method of predicting the likely impact of major land use changes on water quality. There are essentially two approaches to predictive management in common use, extrapolation and modelling (Schofield, 1997). Both approaches are poorly developed in managed forests. The most commonly used method of erosion prediction in both agricultural and forestry environments has been the Universal Soil Loss Equation (USLE) or modified and hybrid forms of the relationship (see Hairsine and Hooke, 1993 for review). Despite modifications to the original formulae for forestry environments (Dissmeyer and Foster, 1980; Rosewell, 1993) there are some inherent problems with the USLE and its use as an erosion hazard prediction tool in these environments. The main problems lie in the exclusion of gullying or mass movement processes; deposition and redistribution processes and the fact that the slope length and steepness factors must be determined only on the area that is contributing runoff. The major limitations of all existing methods of erosion hazard prediction were summarised by Hairsine and Hooke (1993). These include the fact that:

- None of the methods assess the relative importance of different forms of erosion and the user is left to decide what the relative significance of gully, sheet or rill erosion is within a particular land area or region.
- Thresholds are not usually considered.
- There is a lack of dynamic components, including relative capacity to regenerate vegetation and redevelop soil properties.
- The quality of the input data limits the quality of all predictions. It is the understanding of erosion that a method represents that largely determines its utility in predicting erosion and the development of appropriate management strategies. In the absence of a good thorough understanding of the physical processes of sediment transport and delivery, the proliferation of interpretive software such as geographical information systems (GIS) will not improve the quality of predictions.

There is a continuing trend both in Australia and overseas to use quantitative rather than qualitative methods to assess soil erosion hazard and susceptibility at both the regional and local scales. In the United States, a large amount of money and resources has been directed at developing more sophisticated erosion prediction modelling tools (eg Water Erosion Prediction Project WEPP, Robichaud *et al.*, 1993) which require extensive parameterisation. Hairsine and Hooke (1993) concluded from their review that simple empirical forms such as the USLE and its hybrid forms have the advantage of simplicity and higher level of validation and recommended its continued use in forestry environments. The recommendation was based primarily on the lack of input data for the more physically-based models, which are not widely available for Australian forestry catchments. Improved understanding of the physical processes of sediment movement in these environments since this report suggest that these simple relationships are unlikely to accurately predict the likely catchment scale impact.

The lack of a clearly structured framework within which to assess the potential impacts of forest harvesting practices on water quality has seriously limited the usefulness of predictive management over the last 10 years. In the United States, there is greater emphasis on what it is the community wants to protect, and what must be done to ensure protection. Examples of community driven issues are channel destabilisation, increased peak flows, channel sedimentation and removal of stream-side vegetation. Many studies in the United States are specifically designed to examine potential impacts on fish species and ecological habitats (eg many rivers in the Pacific North west of the United States are of high ecological value with respect to salmon breeding or endangered fish species). In Australia, aside from water-drinking standards, there has been little emphasis on thresholds of concern (TOC) or more fundamental questions such as:

- what are the key areas requiring protection ?
- what is the capacity of the system to withstand change ?

In the absence of a clearly defined framework for water quality protection, there has been much emphasis (perhaps over emphasis) on sediment production, which in turn is commonly used as a surrogate measure for turbidity and ultimately in-stream water quality. This occurs in spite of extensive evidence from the literature that the waters draining forested catchments (managed and un-managed) is of a higher standard than those in any other catchment landuse (NSCAI, 1994).

The desire to construct a defensible system of water quality protection has meant that many agencies and land managers continue to pursue the quantitative approach. They require a simple check-list type system that produces a single value that can be documented and legally defensible. The problem to date has been that the use of an empirical relationship such as the USLE in forestry environments is not scientifically defendable. The issue of water quality and forest practices extends beyond sediment production rates and is inherently more a matter of sediment delivery, which the USLE cannot calculate. The following section introduces a selection of assessment procedures used in the United States where the potential impacts of timber harvesting and roading etc are examined within a more structured, holistic framework at the catchment/watershed scale.

3.8.1 A review of selected American Assessment Procedures

The following examples of quantitative modelling approaches adopted in the USA are provided as they represent the leading methods of assessing water quality due to harvesting practices.

1. Water Resources Evaluation of Non-point Silvicultural Sources (WRENSS)

The most complete process-based approach to assessing timber-management impacts is the series of procedures referred to as WRENSS (USFS, 1980; Reid, 1993). This collection presents quantitative evaluation procedures for a variety of water quality impacts including altered flows, sediment and temperature. Pollution by nutrients and chemicals is addressed qualitatively as are changes in dissolved oxygen. Sediment modules include methods for estimating surface and ditch erosion, landsliding, earth flow activity, sediment yield and channel stability. Surface erosion is calculated using a modified USLE and sediment delivery relations and ditch erosion is assessed by calculating permissible velocity. The landsliding module is a step-by-step guide to performing a landslide inventory for an area. Sediment yields are estimated using results of monitoring and process evaluations, and channel stability is indexed by changes in sediment and flow. Each procedure presented in WRENSS was developed by researchers and resource specialists with relevant expertise. Some of the methods have been intensively tested while others have not been validated at all. Many of the methods employed by WRENSS are founded on extensive experiments and large data bases.

2. Equivalent Roading Area (ERA)

The ERA model addresses downstream impacts of timber harvesting generated by several mechanisms. Impact potential is indexed by relating the impacts expected from each activity to that expected from forest roads. The sum of indices for a watershed represents the percentage of basin in road surface that would produce the same effects as the existing or planned distribution of management activities. Indices for different planning options can then be compared to rank their potential for producing impacts. Application of the method first requires identification of important downstream values and the criteria necessary to protect each. In its early application, the model assumes that channel destabilisation is the impact of most concern and that destabilisation occurs primarily from increased peak flows due to soil compaction. The early foundations of the ERA model used the results of a study in southern Oregon that showed peak flow increases in a basin with 12 percent roaded area (Harr *et al.*, 1975) as the basis for identifying both the driving mechanism for change (increased peak flows) and the TOC (12 percent compacted area). However these results were found not to be transferable to California's geology and climate. Ziemer (1981) demonstrated that no significant change in peak flows in a California coast range watershed with 15% of its surface area compacted. In addition because channels respond as readily to altered sediment inputs as to altered flows, selection of increased peak flows as the single driving mechanism does not fully address this issue (Reid, 1993). Management activities are usually planned to maintain a watershed's ERA below an identified TOC. If the threshold is approached or exceeded then activities are reviewed to determine whether they should be delayed or modified or whether existing conditions could be modified to lower the ERA values. A basin is assumed to be healthy again as soon as sub-threshold ERA values are reattained but the recovery times actually required by impacted resources are not considered.

3. R-1/R-4 Sediment-Fish Model

USDA forest service researchers and others developed a model for predicting fish survival as a function of sediment input in the Idaho Batholith. The R-1/R-4 model addresses settings where deposition of fine sediment is the major impact on fish populations and where sediment is eroded primarily by surface erosion on logged sites and roads. Sediment yield is predicted using relations developed from extensive research on landuse erosion rates in the Idaho Batholith. Average loss rates were calculated for roads, logged areas and burnt sites and these are applied to areas of each activity in the watershed to calculate on-site loss rates. A sediment delivery relation from WRENSS, USFS 1980) is used to calculate input to streams and a relation defined by Roehl (1962) allows estimation of delivery to critical stream reaches. As presented the model applies only to the Idaho Batholith because its relationships depend strongly on runoff mode, runoff timing, climate, sediment character, the combination of erosion processes, channel geometry and species of fish. Use of the method in other areas requires remeasurement of each of the component relations. This procedure is one of few however that relate landuse activities directly to a resource response and is unique in its recognition that impact recovery rates cannot be indexed by recovery rates of the driving landuse. Once a channel reach is modified, the new condition becomes the baseline for further changes, and effects that accumulate through time can therefore be predicted.

Current Erosion-Sediment Delivery Hazard System in NSW.

Since 1995 the EPA Pollution Control Licence of NSW required State Forests to assess soil erosion and water pollution hazard using a modified application of the computer program SOILOSS 5.1 developed by the Department of Land and Water Conservation (DLWC) (Rosewell, 1995). This program is based on the Revised Universal Soil Loss Equation, in addition to field assessments of the proportion of dispersible soils within the proposed harvest area. The SOILOSS technology was adopted in the licences because it was the best available technology at the time and offered a hazard assessment model, which could be consistently applied and was auditable. Questions regarding the appropriateness of this method were raised by both conservation groups and scientists in 1996 and a review of erosion hazard assessment procedures was conducted. The result was a series of workshops, which discussed a range of theoretical approaches, and models that could be used to assess soil erosion and water pollution hazard. It was suggested that any new system would need to satisfy including a broadened concept of erosion to include mass wasting and movement; a clearer differentiation of the range of operation types and environments on the basis of inherent risk and utilise a hierarchy of scale for determining where the hazard should be assessed and the resource data collected. A proposed model of Inherent Hazard was developed based on the following three interrelated factors:

- rainfall erosivity;
- slope; and,
- soil regolith stability.

The first two factors are well recognised in soil erosion prediction technology (Wischmeier and Smith, 1984; Rosewell, 1993). The last factor concerning regolith stability is essentially a new approach to hazard assessment but has been adopted in other land management systems (Cline *et al.*, 1981; Turner *et al.*, 1990). The soil regolith cohesion and sediment delivery factors enables an assessment of the erodibility of the material and the delivery potential of this material to streams. Four classes of soil regolith stability were identified which are combined with slope and rainfall erosivity factors to form a inherent hazard matrix system (EPA, 1998). Inherent hazard levels recognise the effectiveness of BMP's and the need to provide additional restrictions in accordance with high-risk environmental factors such as slope, rainfall or soil stability. This new method of identifying inherent risk using a combined sediment generation and delivery method substantially improves our ability to target high risk areas - not just high risk in terms of erodibility but also in terms of delivery to streams.

3.9 FINDINGS OF THIS REVIEW

3.9.1 Knowledge Gaps

This review reported the literature findings with respect to observed impacts in water quality due to timber harvesting activities including road infrastructure. A number of important issues, however, remain relatively unexplored in the literature. These focus primarily on the lack of studies examining the issues at a range of temporal and spatial scales. The following issues in particular require further attention.

Temporal trends in impact assessment.

The magnitude of disturbance and sediment generation is considerably greater on recently constructed roads than stable well-established surfaces, although data in the literature comparing this temporal trend are scarce. There are few new roads currently being constructed for forestry operations due to the economic expense and the presence of a relatively large existing infrastructure in many catchments and regional forest areas. The major impact of road infrastructure in Australian forested catchments, therefore, is likely to have occurred some 30 years or more ago when large areas of forest roads were built to meet increased harvesting demands. Possible impacts may have included increased channel destabilisation, in-stream storage of both coarse and fine material, and siltation of estuaries. These impacts may be emerging as major issues of concern in some catchments today due to the rate of temporal response and readjustment of the channel system. The large increases in sandy bed load material observed in many of south eastern NSW streams may be a function of 'historic' landuse impacts or more-recent landuse changes such as forest roading, and the clearing of forests for agriculture etc. The community remains divided with regard to their perceptions, many have anecdotal evidence that relates to a particular time period, and scientists have failed to adequately address the issue through well-defined, large-scale catchment monitoring studies.

Spatial-scale of analysis.

The review also pointed to the scarcity of catchment or regional scale analysis of potential impacts. Whilst acknowledging the problems with in-stream monitoring studies, there is a clear need to redefine the objectives of water quality monitoring programs to address specific issues. This forces both scientists and interested parties to identify the areas that require protection and the means to ensure their protection. This is not a simple task but is one that researchers and community groups must make if we are to progress in our development of acceptable water values. The literature overwhelmingly suggests that even if small-scale increases in stream turbidity are observed these are short-lived (within the time frame of 2-3 years) and that the persistent effects of increased sediment yields are rarely reported. There must also be increased public awareness that stream turbidity is a natural phenomenon that even in pristine forests, reflects the dynamic processes of sediment transport and channel adjustment. There is an urgent need for clearer, well-defined thresholds of concern that can be used to manage and regulate these systems. These thresholds must be established for all aspects of stream health and not just sediment loads or turbidity but also biological indicators. In Australia, there are no ‘baseline’ data sets of biological and chemical indicators of stream health. Consequently, studies examining the potential impacts of land use change on stream systems have limited opportunity to assess the magnitude of the impact.

Predictive tools – the way forward ?

The third aspect that remains unresolved from the literature is the type of predictive tools that should be applied to the management of harvesting/roading practices in forested catchments. The debate about simple empirical relationships or sophisticated models is likely to continue. The first step in evaluating this question for Australian forested catchments lies in data assimilation and archiving. The common use of GIS by many of the state agencies should mean that it is now possible to collate available soils, topographic, infrastructure data and develop catchment-scale characteristics. It is clear, however, that predictive tools must be clearly linked to identified areas or thresholds of concern; what it is that requires protection and the acceptable limits of change.

3.9.2 Recommendations for Forest Management Practices

It is clear from this, and other reviews (eg Dargavel *et al.*, 1995), that the most important issues in relation to water quality relate to the standard of forest management practices. Improvements in the standards and guidelines for harvesting operations can only improve the level of protection afforded to water quality in these catchments. A number of issues emerge from the review that could be incorporated directly into current practices.

- Road use is a critical variable in explaining enhanced sediment production rates. If roads are not being used within a catchment then there should be serious consideration given to the rehabilitation of these surfaces through regeneration and drainage. There are many catchments, which retain a legacy of road pathways from pervious landuse activities but remain as a potential source of sediment. Considerable effort should be made to remove/rehabilitate old roads from catchments.
- The most persistent and threatening impact of sediment delivery due to roading relates specifically to gullying and channelisation at road drainage outlets. Once gullies have

formed there is limited, if any opportunity, to remediate these features so that they remain a persistent threat to in-stream water quality. Every opportunity should be taken to ensure that gullying does not occur through appropriate spacing of drainage structures.

- Finally, it should be recognised that the most dramatic impacts on water quality will come about in response to the most dramatic land use changes. Removing trees by slash and burn methods on a broad-scale nature, or conversion to pasture or annual crops all decrease the frequency of deep woody roots and increases the probability of accelerated mass erosion (Ziemer and Swanston, 1977; Schofield, 1996). The development and refinement of BMP’s within the forest industry over the past 10 years has significantly improved methods of timber harvesting, in particular, selective logging on an alternate coupe basis and the introduction of the recent inherent hazard system. Continuing efforts must be applied to developing environmentally sound practices of timber removal.

4. MODELLING FRAMEWORK

4.1 INTRODUCTION

One of the principal objectives of this project was to develop a methodology for modelling the impact of logging on water quality and quantity. The general process of model development follows the suggestions of Grayson and Nathan (1993), in which the models were developed specifically to suit the project objectives at a complexity commensurate with the available data. The models developed for the study are conceptually simple. While this lack of modelling complexity partly reflects the limited time available, the governing constraint is that there is not the data available to apply and validate more complex models at the required spatial and temporal scales.

Importantly, development of the modelling methodology was subject to the following two major constraints:

- the available time to identify, collate and process the necessary inputs, and to develop and apply the models, was around six weeks; and,
- the modelling framework had to be applicable to all areas covered by the comprehensive regional assessment process for forests in New South Wales.

Detailed descriptions of model development are provided in Section 5 and Section 6. The following sections describe the selection of catchments used to develop and apply the models, as well as the nature of inputs common to the assessment of both water quantity and water quality impacts; details of the modelling scenarios to be considered are described, and the context in which the model results can be incorporated in the comprehensive regional assessment process is also discussed.

4.2 SELECTION OF CATCHMENTS

Considerable effort was spent on identifying suitable catchments that could be used to assess the impacts of logging activities. The catchments were selected using GIS tools and information on stream gauging.

The salient selection criteria were biased towards the availability of suitable information rather than representativeness. The primary criterion used was the availability of information to characterise the hydrology of the streams as they leave the State Forest area, and at some point downstream in agricultural areas. This enables the modelled impacts in yield and water quality to be place in context of the baseline downstream conditions. A schematic of the desired arrangement is provided in Figure 4.A. Throughout this document the gauging station located immediately downstream of the forest is referred to as being "downstream of forest", and that further downstream of both the agricultural and forest land uses is referred to as being "downstream of mixed land use".

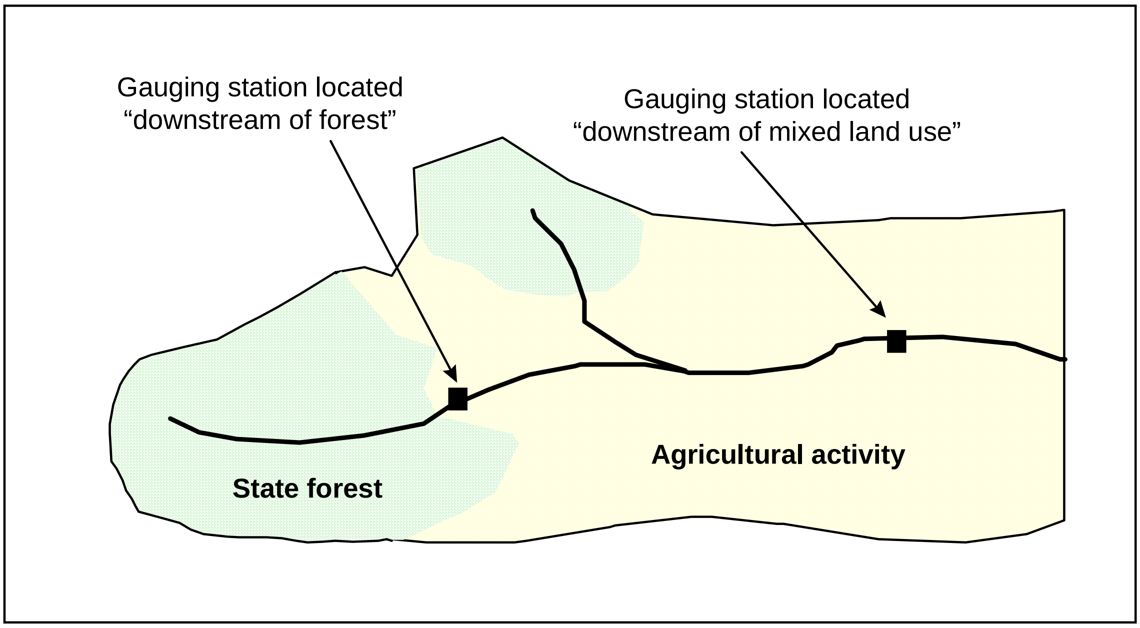

FIGURE 4.A SCHEMATIC ILLUSTRATION OF SALIENT CATCHMENT SELECTION CRITERION

A total of 7 catchments were selected from the Upper North East (UNE), Lower North East (LNE) and Southern RFA Regions. The location of the catchments is shown in Figure 4.B, and Table 4.A lists the selected catchments and the corresponding state forests. A map of each catchment is provided in Appendix C which shows the catchment boundary, state forest boundaries, stream network and streamflow gauging stations.

Table 4.B lists the gauging stations identified as being immediately downstream of the forest, and those located further downstream of the agricultural activity. This table also details the total area of the catchment and that of the State Forest that lies upstream of the gauge; these areas are not necessarily the same as in some cases the upstream area includes National Parks and some small amount of agricultural activity. Also listed are the corresponding areas lying upstream of the gauge representing mixed land use. The area of State Forest lying upstream of the two gauges is not necessarily the same as in some cases tributaries draining additional forest area enter the mainstream below the upstream gauge (as shown in Figure 4.A).

Table 4.C lists the period of record and mean annual flow for the selected gauging stations. Where the periods of record were not concurrent, the mean annual flow calculated for the gauge with the shorter period was adjusted to reflect the long-term flow conditions estimated using the data at the other gauge.

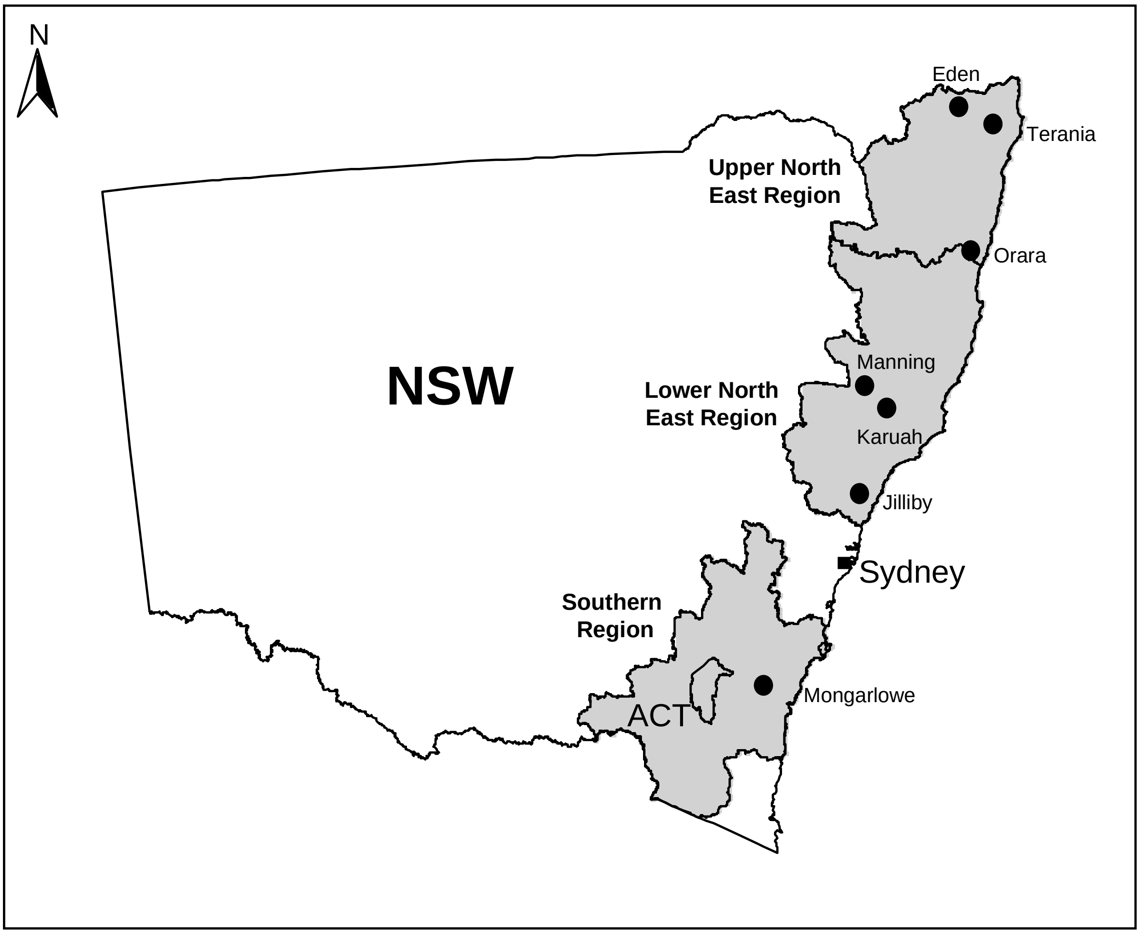

FIGURE 4.B LOCATION OF SELECTED CATCHMENTS

TABLE 4.A SELECTED CATCHMENTS

Catchment Name	CRA Region	State Forest Identification Number	Mean Annual Rainfall (mm)
Eden Creek	UNE	343	1240
Terania Creek	UNE	173, 3	1830
Orara Creek	UNE	535, 612	2070
Manning River	LNE	276, 977	1090
Karuah River	LNE	280, 292, 293	1270
Jilliby Creek	LNE	124, 281	1250
Mongarlowe River	Southern	144, 1009	920

TABLE 4.B STREAMFLOW GAUGING STATIONS FOR SELECTED CATCHMENTS

Catchment Name	Downstream of forest			Downstream of mixed land use		
	Gauge Number	Catchment area (km²)	u/s forest area (km²)	Gauge Number	Catchment area (km²)	u/s forest area (km²)
Eden Creek	203018	32	19	203032	202	46
Terania Creek	203036	36	31	203022	156	37
Orara Creek	204047	19	19	204025	135	76
Manning River	208002	52	40	208012	480	101
Karuah River	209001	203	158	209003	974	158
Jilliby Creek	211004	8	8	211010	92	53
Mongarlowe River	215007	45	41	215005	417	74

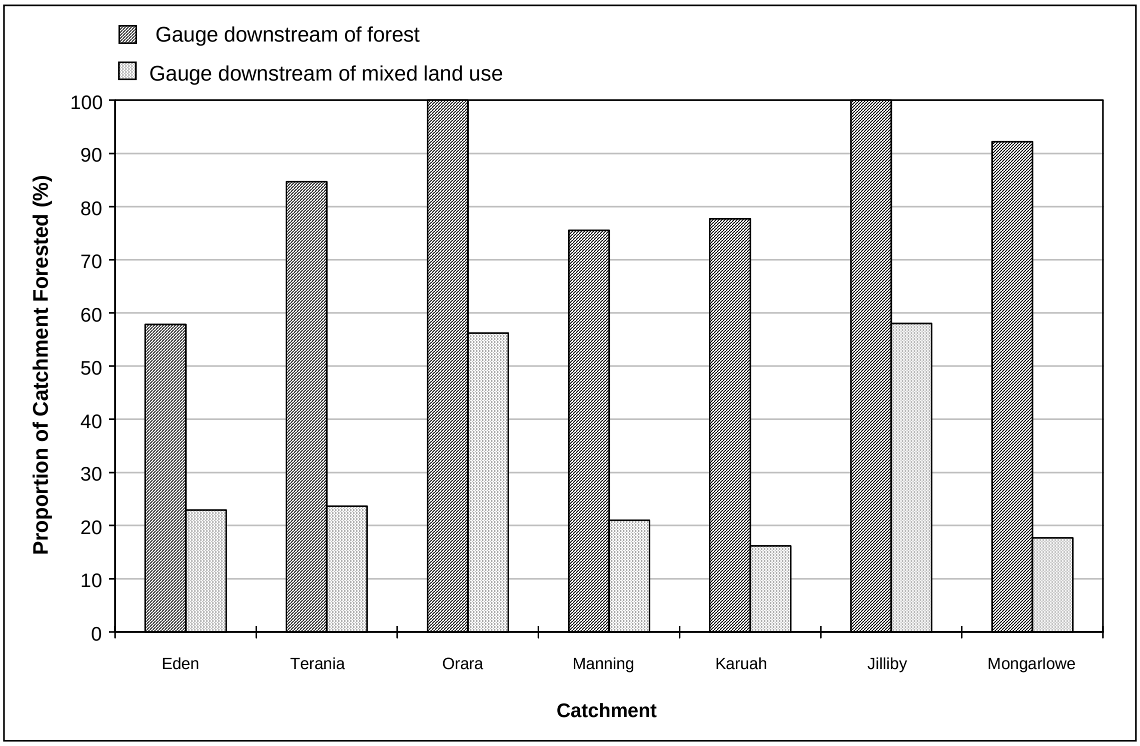

FIGURE 4.C PROPORTION OF CATCHMENT COVERED BY STATE FOREST

TABLE 4.C SUMMARY OF STREAMFLOW DATA

Catchment Name	Gauging Station	Period of Record		Mean Annual Flow (ML)
		Start	End	
Terania Creek	203036	1972	1979	30000
	203022	1967	1983	146000
Eden Creek	203018	1967	1986	17500
	203032	1970	1985	80000
Orara River	204047	1970	1979	35000
	204025	1925	1996	126000
Manning River	208002	1958	1981	39000
	208012	1964	1986	110000
Karuah River	209001	1945	1982	145000
	209003	1968	1997	237000
Jilliby Creek	211004	1961	1990	1300
	211010	1973	1995	24000
Mongarlowe River	215007	1950	1953	29000
	215005	1945	1986	116000

4.3 MODELLING SCENARIOS

Once the catchments were identified it was necessary to determine realistic future management scenarios for these catchments. Thus for each catchment information was sought from the regional planning managers on:

- plausible logging scenarios in terms of percentage canopy removal; and,
- information on existing distribution of forest age.

The adopted scenarios are not intended to pre-empt the results of the CRA process but rather provide reasonable management scenarios on which to base the modelling. The actual logging scenarios to be implemented within these catchments will depend on the CRA process and thus will differ from those adopted for the purposes of preliminary evaluation.

The state forests and the estimated net harvestable area are shown in Table 4.D for each catchment. The net harvestable area was estimated after consultation with regional forest managers.

TABLE 4.D LOGGING SCENARIOS ADOPTED FOR MODELLING

Catchment	State Forests Reference No.	Net Harvestable Area
Eden	343	46%
Terania	173, 3	46%
Orara	535, 612	46%
Manning	276, 977	42%
Karuah	280, 292, 293	34%
Jilliby	124, 281	47%
Mongarlowe	144, 1009	50%

The adopted logging scenarios are shown in Table 4.E. For a given period in years the activity is split into thinning and also group selection. For each activity the percentage of the total forest that is logged annually is shown along with the total removed over the indicated period. The nominal age of the trees targeted for each activity is also shown with the indicative range indicated afterwards in brackets. The range of forest ages was necessary to provide sufficient forest to satisfy the adopted scenario.

For example, for Eden during the first 17 years of the scenario 0.59% of the forest is thinned each year, representing a 10% canopy removal over the 17 year period. The trees selected for thinning have a nominal age of 25 years. During the following 30 years 0.70% of the forest is logged each year by group selection, representing 21% of the total forest area. The trees selected for harvesting have a nominal age of 60 years. The last 10 years of the scenario is for thinning 0.50% annually for a total canopy removal of 5% over the 10 year period, with a nominal age of 25 years.

The different period of thinning and group selection are shown in Figure 4.D. The scenarios for Manning, Karuah and Jilliby have periods where thinning and group selection are undertaken concurrently.

Unfortunately no catchment-specific logging scenarios were provided for any of the catchments in the UNE Region. The logging scenarios adopted for these catchments were therefore based upon the scenario provided by the Northern River Region for the modelling work undertaken by State Forests for the Rocky Creek Dam catchment. The scenario should be applicable for the Terania catchment (as the Rocky Creek is a tributary of Terania Creek), but is likely to be less relevant for the Eden and Orara catchments.

TABLE 4.E LOGGING SCENARIOS ADOPTED FOR MODELLING

		Thinning			Selective logging / group selection		
Catchment	Period (years)	Rate (%/year)	Total Canopy Removed (%)	Age Group (years)	Rate (%/year)	Total Canopy Removed (%)	Age Group (years)
Eden	17	0.59	10	25 (20 - 80)			
	30				0.70	21	60 (45 - 120)
	10	0.50	5	25 (20 - 40)			
Terania	17	0.71	12	25 (20 - 60)			
	30				0.70	21	60 (45 - 120)
	10	0.50	5	25 (20 - 40)			
Orara	17	0.71	12	25 (20 - 70)			
	30				0.70	21	60 (45 - 120)
	10	0.50	5	25 (20 - 70)			
Manning	15	0.99	15	30 (10 - 35)	0.99	15	110 (40 - 130)
	15	0.99	15	20 (10 - 25)	0.33	5	60 (30 -110)
	60	0.99	60	20 (10 - 25)			
Karuah	10	0.80	8	20 (10 - 40)	1.00	10	90 (40 - 140)
	10	0.80	8	20 (10 - 40)	1.00	10	90 (40 - 140)
	70	0.80	56	20 (10 - 40)			
Jilliby	10	0.50	5	30 (20 - 40)	1.00	10	100 (80 - 140)
	10	0.50	5	30 (20 - 40)	1.00	10	100 (80 - 140)
	70	0.50	35	25 (20 - 30)	1.00	70	100 (30 - 140)
Mongarlowe	25	0.6	15	70 (40 -80)			
	25	0.6	15	70 (30 - 100)			
	25				2	50	90 (20 - 120)

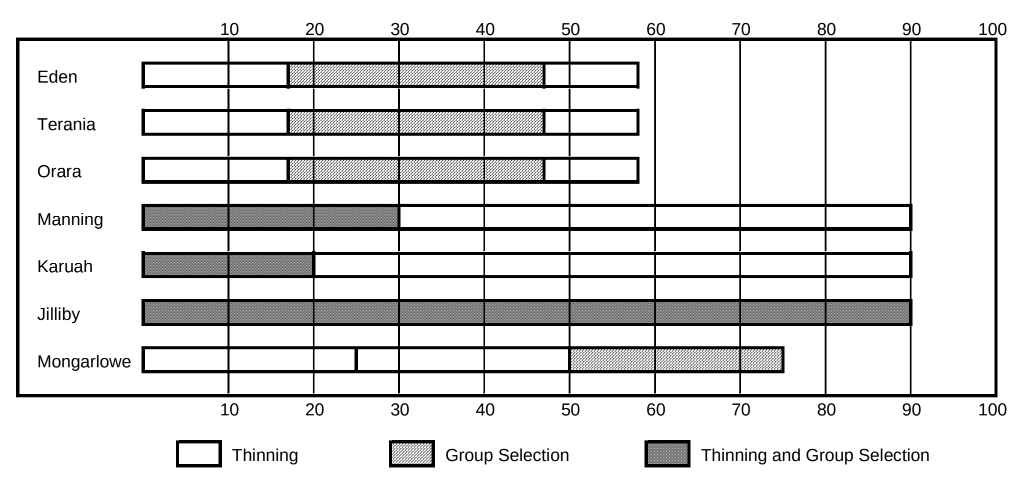

FIGURE 4.D SEQUENCE OF ADOPTED LOGGING ACTIVITIES.

4.3.1 Current Forest Age Profile

The information on the age-profile of the existing forest was provided by G Hall (*pers. comm.*) who analysed the CRAFTI (Comprehensive Regional Assessment Photographic Interpretation – Upper Northeast Region) and BOGMP (Broad Old Growth Mapping Project 1996 – Lower Northeast Region) aerial photographic interpretation projects for the CRA process

The adopted forest age profiles are shown in Table 4.F. Information on forest history was not available for forest in the Southern Region and therefore the profile for the Mongarlowe Catchment was adopted after discussions with State Forests and should only be considered as approximate.

TABLE 4.F FOREST AGE PROFILES ADOPTED FOR MODELLING

Age Range	Proportion of forest within given age range (%)						
(years)	Eden	Terania	Orara	Manning	Karuah	Jilliby	Mongarlowe
0-10	2	0	0	36	10	1	0
10-20	1	10	9	6	11	28	5
20-30	1	10	9	6	11	28	5
30-40	1	7	8	1	1	0	30
40-50	1	7	8	1	1	0	30
50-60	32	31	27	7	21	3	5
60-70	32	24	19	9	24	13	5
70-80	1	0	1	3	4	10	5
80-90	1	0	1	3	4	10	5
90-100	2	1	1	5	2	1	5
100-120	4	1	2	10	4	3	5
>120	22	8	14	13	9	4	0

4.4 STRESS INDICATORS FOR DOWNSTREAM CATCHMENTS

The interim results of the Stressed Rivers Assessment Process can be used to place the modelled changes in context with the downstream baseline conditions and to assist in the identification of forests which have downstream areas which are likely to be sensitive to changes in yield and water quality.

The NSW Government initiated the Stressed Rivers Assessment Process as a rapid assessment of the current and potential future stress of unregulated rivers. This assessment was carried out by regional scientists and technical experts with technical panels (consisting of DLWC, EPA, NSW Agriculture, NPWS, Fisheries).

Some 680 unregulated subcatchments were defined and each subcatchment was categorised in terms of:

- hydrology stress rating;
- environmental stress rating;

- overall stress classification; and,
- full development stress classification.

An evaluation of environmental and conservation status was also undertaken as part of the stressed rivers approach. Indicators of environmental values were developed and assessed by DLWC in conjunction with NSW National Parks and Wildlife Service and NSW Fisheries.

The classification of stress ratings and the identification of subcatchments with environmental values or conservation status are presented in the Stressed Rivers Assessment Report (DLWC, 1998). The assessments are only preliminary and are currently being refined, however at present they are considered to provide the best indicator of the condition of downstream catchments.

The stress indicators from the Stressed Rivers Assessment Process for the selected catchments are shown in Table 4.G. For a number of catchments the hydrologic stress is expected to increase from the current assessment when allocated water is fully utilised as indicated in the 'Future' column. All of the catchments are assessed to be under 'Medium' environmental stress apart from Jilliby which is assessed as 'High'.

TABLE 4.G STRESS INDICATORS FOR SELECTED CATCHMENTS

	Hydrology Stress Rating		Environmental	Identified Conservation Values	
Catchment	Current	Future	Stress Rating	NPWS	Fisheries
Eden	Low	High	Medium	No	Yes
Terania	Low	High	Medium	Yes	Yes
Upper Orara	Medium	High	Medium	Yes	Yes
Manning	Low	Low	Medium	No	Yes
Karuah	Medium	Medium	Medium	Yes	No
Jilliby	High	High	High	Yes	No
Mongarlowe	Low	Low	Medium	No	No

The results of the stressed rivers project are useful in that they give an indication of the condition of downstream catchments. A series of maps was therefore produced which show for each CRA region the location of the state forests and the preliminary assessment of hydrologic and environmental stress of the downstream subcatchments. The maps can be used to assist in the identification of forests which have downstream areas which are likely to be sensitive to changes in yield and water quality.

The information on Stressed Rivers was combined with the State Forest boundaries within each of the CRA regions. The resulting maps are provided in Appendix D, and they can be used to assess the catchment conditions downstream of the forests in terms of:

- hydrological stress;
- environmental stress; and,
- conservation significance.

4.5 APPLICATION TO OTHER AREAS IN THE CRA REGIONS

As discussed in Section 4.1, one of the primary constraints on model development was that the methodology should be applicable to all areas within the CRA regions. While a detailed description of the modelling methodology is presented in Section 5 and Section 6, it is worth summarising here the sequence of steps and the nature of the inputs required to apply the models to any area in the CRA regions. The sequence of steps and input data required can be summarised as follows:

1. Define catchment area of forest
2. Obtain logging scenario for the forest, which should include specification of the:
   - proportion of gross forest area that is harvestable
   - sequence of logging activities (e.g. thinning, selective logging, group selection)
   - area of forest subject to different logging activities
   - range of forest ages subject to different logging activities
   - rotation cycle of logging sequence
3. For assessment of impacts on water quantity, it is necessary to obtain additional information on:
   - mean annual rainfall for the catchment
   - initial age profile of the forest
4. For assessment of impacts on water quality, it is necessary to obtain additional information on:
   - GIS information on drainage lines (including “zeroth order” streams), the road network (including road classes), buffer strip allowances surrounding the drainage lines, and Inherent Hazard Category;
   - derivation of site-specific Sediment Delivery Ratio (SDR) based on analysis of drainage and road network densities (as described in Section 6).
5. The modelling approach as described in Section 5 and Section 6 can then be applied to the area of interest using the above input data.

The above inputs are readily available for the three CRA regions considered in this study. The only exception to this is that detailed information on drainage density and Forest Management History is not available for the Southern region. The latter information could be obtained using judgement and local knowledge, and the need for the former could be obviated by using SDR data obtained directly from catchments in the northern regions, or else by developing drainage density adjustment factors.

The modelling results can be expressed in terms of differences to the current baseline, or else in absolute terms (ie in streamflow volume, ML, or stream sediment load, mg/l). The modelling results can most easily be determined for a point immediately downstream of the forested catchment, though the significance of the impacts on downstream catchments can be assessed using the stressed river indicators provided in Appendix D.

It must be stressed that the major output of this project is a modelling framework rather than a set of results that can be directly transposed to any region. While the modelling approach has been used to assess the impacts on a range of test catchments, it is recommended that the modelling limitations identified as being able to be resolved in the short term should first be examined in some detail.

It should also be stressed that there is considerable uncertainty in the estimates. Some of the modelling inputs and parameters are based on published literature, and others are based on speculation. Model parameterisation could be altered to incorporate better information when it becomes available, and some of the more speculative aspects could be modified to be consistent with a consensus view.

The uncertainty of the estimates largely stems from a lack of information. Our ability to develop sophisticated models is far in advance of the level of information required to validate or apply the models. The paucity of information thus limits model development in two ways: (i) there is insufficient data with which to parameterise (and hence validate) models for a range of catchment conditions, and (ii) there is insufficient physical and hydrometeorological data available to apply the models to all the regions of interest.

It is considered, however, that the uncertainty of the estimates does not detract from the ability of the models to provide information on the *relative ranking* of proposed measures. While the absolute magnitude of the estimates may be uncertain, the models do codify our current best understanding of the different factors that influence water quantity and quality within the limitations of current data availability. The models thus provide a robust, credible, and objective basis for evaluating the impacts of logging, particularly if used to rank proposed activities in terms of relative disadvantages and merits.

5. YIELD MODELLING

5.1 GENERAL OVERVIEW

The impact of logging activities on water yield is variable, and is dependent upon the degree of forest disturbance and the forest age, as well as the complex interactions between climate, soils, vegetation and topography. Water yield changes are linked to forest growth, and thus the impacts are very long term in nature. While considerable information on water yield impacts has been collected for several Melbourne water supply catchments, there is a dearth of information that is directly relevant to NSW forests.

The overall approach is to adopt the form of yield response observed in the Melbourne water supply catchments, but to select parameters based on the limited evidence collected to date from NSW catchments. In order to characterise the expected yield changes the available data was standardised by annual rainfall and the proportion of canopy removal. In essence, changes in annual yield response are estimated to be a function of the fraction of canopy removed, time since logging, annual rainfall, age of forest, and region. Review of the literature and analysis of the available data indicates that it is not possible to reliably assess the impacts on the seasonality or frequency of flows, and thus the water quantity impacts are restricted to characterising changes in annual yields only.

The actual changes in yield are estimated for each specific site using the following steps:

1. A plausible logging scenario is defined that considers the rate of logging, the nature and time sequence of the activities (eg thinning, selective logging, group selection), and the proportion of the forest available for logging.

2. Information is collated for the catchment on mean annual rainfall and current age profile.

3. A computer model is used to simulate the impacts on water yield arising from application of the plausible logging scenario; the computer model factors the response developed for assessing the impacts arising from the clear felling of an old-growth forest to reflect the degree of canopy removal and the age of the forest being logged.

4. Yield changes corresponding to the lumped response of the whole forest under consideration are reported on a per unit area basis for the following components:
    - the combined effects of forest growth and logging
    - the effects of forest growth only (the “do nothing” scenario)
    - the effects of logging only (derived as the difference between the previous two components).

    In addition to assessing the impacts of logging on the current forest, the yield changes are also provided for the case in which it is assumed that the logging scenario is applied to an old growth forest. The change in average age of the harvestable area and total forest due to logging is also tracked through time.

5. The yield changes per unit area are converted to streamflow volumes, and are compared to current conditions at the downstream boundary of the forest, as well as for a site further downstream that encompasses some agricultural activity.

Details of the plausible logging scenarios are provided in Section 4.3, and a description of the modelling components and their limitations are provided in the Sections 5.2 and 5.4. The results of the analyses undertaken are presented in Section 5.5.

5.2 MODELLING COMPONENTS

5.2.1 General

The modelling approach can be divided into the following four components:

- definition of yield response curve for clear felling of old-growth forest;
- the influence of average annual rainfall;
- the influence of the proportion of canopy removed;
- the influence of forest age; and,
- consideration of sequence of operations.

The following sections describe the above components in some detail, and these are followed by a discussion of the limitations of the approach.

5.2.2 Yield response curve

The overall form of the adopted relationship is based on the response observed in the Melbourne water supply catchments (the “Kuczera” curve), though it is modified to be consistent with the limited evidence available from NSW forests.

The Kuczera (1985) curve represents the yield response resulting from the clear-felling of an old-growth Mountain Ash forest in the Melbourne Water supply catchments. As originally defined, the curve describes a decline in water yield to near half its old-growth value by around 30 years of age, followed by a gradual recovery back to old-growth conditions over the next 50 to 150 years. The original Kuczera curve was later modified (eg Cornish, 1996) to incorporate an initial increase in yield for a short period immediately following forest disturbance.

The Melbourne Water supply catchments are not representative of catchment conditions found in NSW (with perhaps the possible exception of the Picaninny catchment; see Vertessy et al, 1998), and accordingly the Kuczera yield response curve cannot be adopted directly. A limited amount of streamflow data has been collected for two forested regions in NSW that have been subjected to logging (Cornish, 1991, 1993, 1997; Cornish and Vertessy, 1998). The data collected provides information on the magnitude of the initial increase in yield, and some information on the expected declines in water use. No data has been collected to date in NSW that clearly confirms the maximum yield deficit, and no information is available on the length of time required for the forest to return to old-growth conditions. Thus, while the NSW data provides useful information on the likely magnitudes of the initial increase, only limited information is available on the likely magnitude of the maximum yield decrement, and no information at all is available on the likely length of period required for the forest to return to old-growth conditions. In the absence of any other information it is necessary to assume that the recovery period subsequent to the maximum yield deficit is similar to that proposed by the Kuczera curve.

Two characteristic curves were derived, one representing conditions in the Upper North East and Lower North East regions (collectively referred to here as the Northern region), and one for the South Region. The curve for the Northern region was developed using results obtained from the Karuah catchments (Cornish and Vertessy, 1998), which have a mean annual rainfall of around 1600 mm. The adopted relationship is illustrated in Figure 5.A. It is seen that the initial yield increase following clear-felling is around 450 mm, and this increase reduces to zero after around 5 years. A maximum deficit of around 500 mm is reached after 22 years, and this reduces to near old-growth conditions over the next 100 year period.

The curve for the Southern region was developed from results obtained from the Yambulla/Wallagaraugh catchments (Cornish, 1991, 1993, 1997), which have a mean annual rainfall of around 1000 mm. For the Southern region, it is seen that the initial yield increase following clear-felling is around 350 mm, and this increase reduces to zero after 7 years. A maximum deficit of around 250 mm is reached after 22 years, and this also reduces to near old-growth conditions over the next 100 year period.

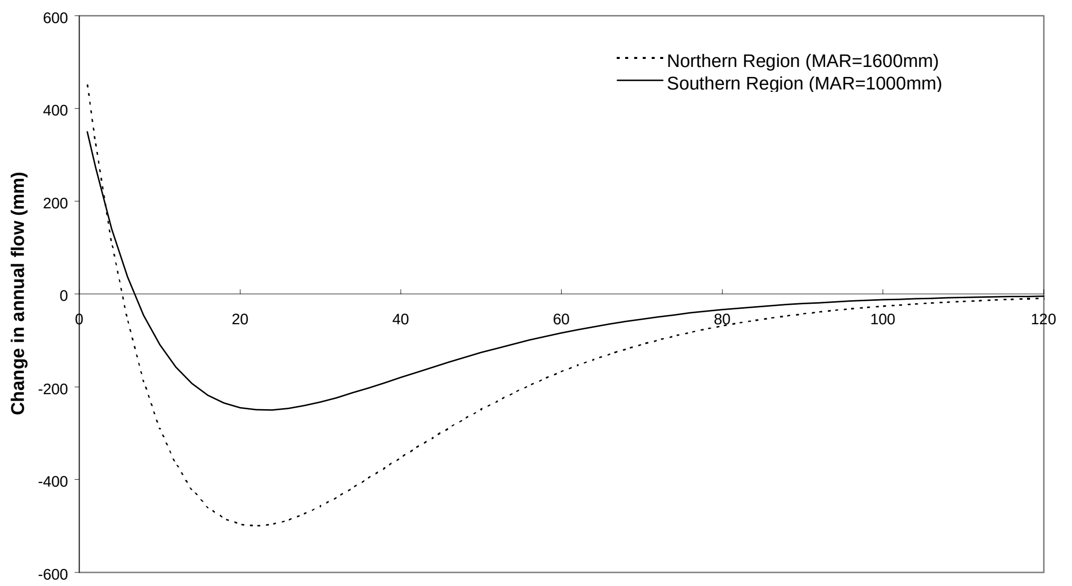

FIGURE 5.A CHARACTERISTIC YIELD RESPONSE CURVES FOR NORTHERN AND SOUTHERN REGIONS

It is possible that the form of the adopted relationship slightly underestimates the length of time of initial yield increase, and overestimates the length of time taken to reach a maximum deficit, but with the paucity of data it is not possible to confidently quantify these differences. Also, it should be recognised that the nature of the yield recovery characteristics approaching old-growth conditions is speculative as there is no data available for NSW forests that cover this period, and indeed the data available for the Melbourne Water catchments is limited to a maximum of 50 years.

Transposition of this relationship to predict yield changes in other catchments is a gross simplification of reality. Some of the factors that are likely to be important but are ignored include:

- tree species and forest structure;
- soil type and depth;
- topography and aspect; and,
- climate.

There are a large number of other factors that are perhaps of secondary importance. For example, the characteristics of the yield recovery after the maximum deficit is largely based on the regrowth of Mountain Ash in the Melbourne Water catchments after the 1939 fires. These forests were not subject to optimal thinning practices, and thus, aside from the differences noted above, the manner in which forest structure changes with time may also be different.

Some discussion regarding the difficulty of incorporating the above factors into the transposition to other forests is provided in Section 5.4.

5.2.3 Influence of mean annual rainfall

The forested catchments within NSW receive widely differing amounts of annual rainfall. While there are too few yield-response studies in NSW to characterise the influence of differences in mean annual rainfall on catchment yield after logging disturbance, it does appear reasonable to speculate that the magnitude of yield response is dependent on mean annual rainfall. In order to incorporate the influence of rainfall, it is assumed that:

- the maximum increase in yield immediately following logging is directly proportional to rainfall as the proportion of rainfall excess for a given set of catchment conditions is directly function of the incident rainfall; and,
- the maximum deficit in yield is also directly proportional to rainfall as it is assumed that water consumption by the biomass is optimised to suit ambient rainfall conditions.

The first assumption is reasonable if it is accepted that the processes that contribute to the generation of rainfall excess are independent of changes in annual rainfall, and this is supported by the available evidence (Bosch and Hewlett, 1982; Schofield, 1996). No information is readily available to substantiate the latter assumption, though it is adopted for both expedience and because it is considered reasonably plausible.

The main corollary of the above assumptions is that the characteristic yield response curves (Figure 5.A) are directly proportional to rainfall. For example, if the maximum increase in yield for a 3 year old forest is 200 mm for a mean annual rainfall of 1000 mm, then the yield increase for a forest subject to a 20% higher rainfall is simply 20% greater (ie 240 mm). Conversely, if the corresponding yield deficit for a 15 year old forest is 200 mm, then the yield deficit for a catchment with 20% more rainfall is also 20% greater (ie 240 mm). By way of further illustration, the yield response curves for the northern and southern regions are illustrated in Figure 5.B.

Finally, it is worth stressing that the model only provides estimates of yield response due to average rainfall conditions; year to year variations in rainfall are not incorporated.

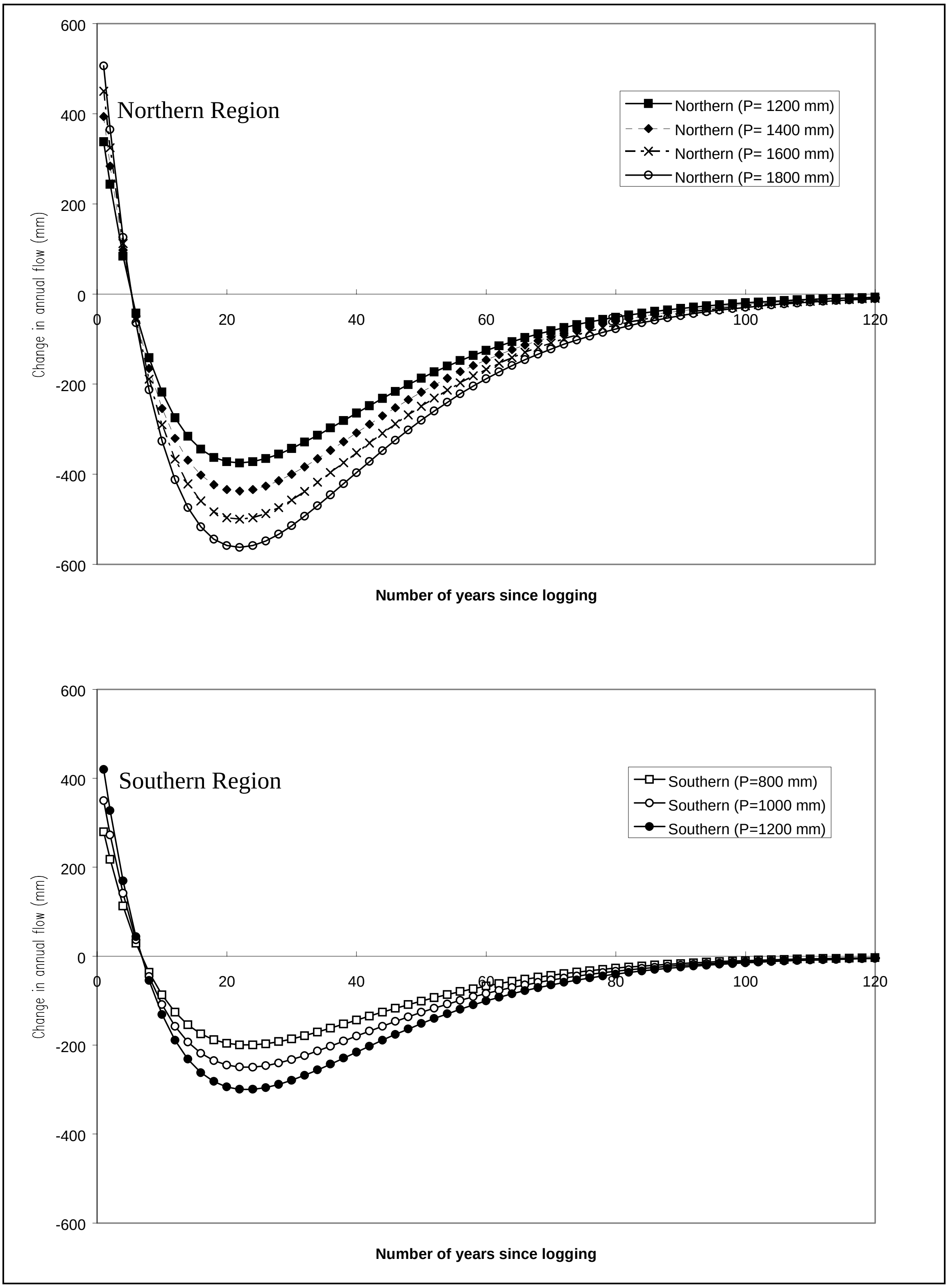

FIGURE 5.B ILLUSTRATION OF VARIATION OF YIELD RESPONSE CURVES WITH MEAN ANNUAL RAINFALL FOR BOTH NORTHEN AND SOUTHERN REGIONS

5.2.4 Influence of forest age

As discussed above, the yield-response characteristics defined in Figure 5.A and Figure 5.B reflect the changes arising from logging an old-growth forest, and are not directly applicable to the logging of new growth forests that are growing more vigorously. However, the yield response curve can be shifted in time to ensure that the maximum impact associated with senescent growth removal is appropriately adjusted to reflect the reduced impact of new-growth forest removal. A schematic representation of this adjustment is shown in Figure 5.C.

It is seen that in order to relate the impacts to a forest of a different age, the origin is shifted to intersect with the yield response curve corresponding to the old-growth forest. This shift in origin merely represents a difference in datum, and does not involve any assumption regarding hydrologic processes. In the example shown in Figure 5.C, the initial increase in yield following clear felling of an old growth forest is around 350 mm. This difference, when calculated relative to the yield response of a 40 year old forest, is 200 mm greater; thus, the increase in yield following the clear-felling of a 40 year old forest is calculated to be 550 mm.

This simple concept of changing the datum allows the impacts of logging to be calculated for a forest of any age. Once the age profile of a forest is determined, this approach allows the impacts of logging to be compared to either current conditions, or to that of an old-growth forest.

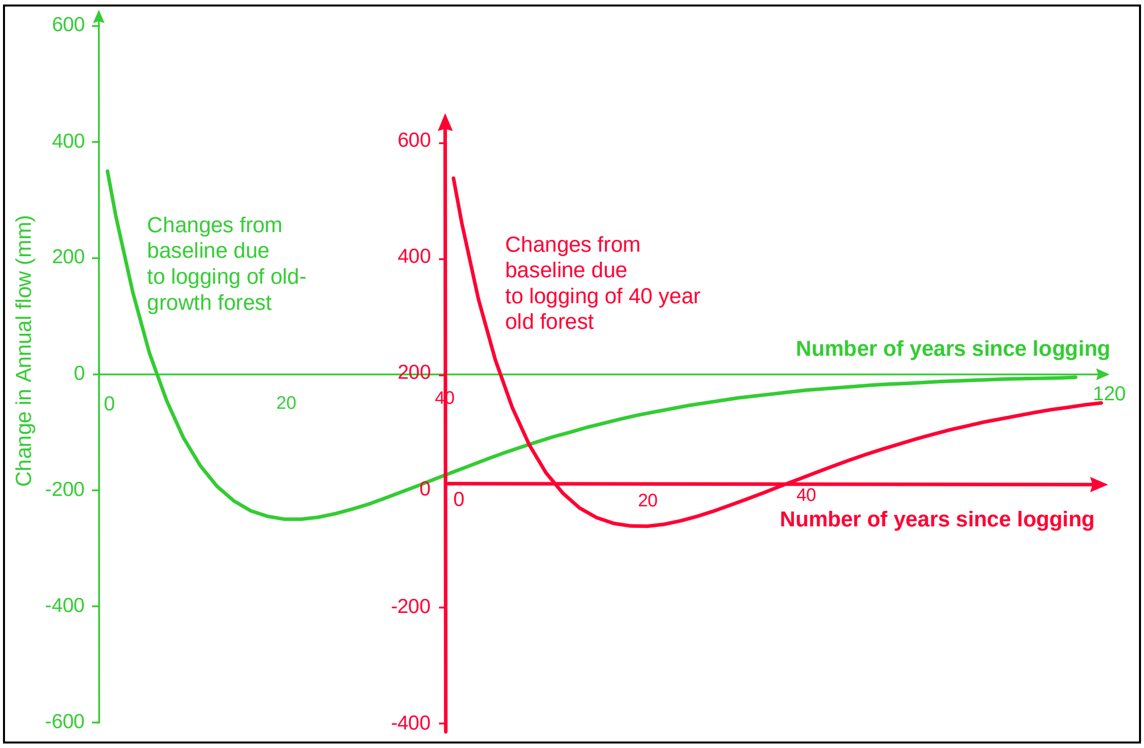

FIGURE 5.C SCHEMATIC ILLUSTRATION OF THE MANNER IN WHICH THE YIELD RESPONSE IS CALCULATED FOR A FOREST OF A GIVEN AGE (EXAMPLE IS SHOWN FOR A 40 YEAR OLD FOREST).

5.2.5 Influence of the proportion of canopy removed

The yield-response characteristics defined in Figure 5.Aand Figure 5.B reflect the changes arising from the clear-felling of an old-growth forest. There is some evidence to suggest (eg Bosch and Hewlett, 1982; Schofield, 1996) that changes in yield are directly proportional to the fraction of the canopy removed, and this assumption is commonly used to help standardise the results from catchments that have been subjected to different degrees of canopy removal. Accordingly, for this study it is assumed that the yield response curves are directly proportional to the fraction of the canopy removed. It is important to note that it is not possible to differentiate between the impacts of different management practices that involve the same degree of canopy removal.

5.2.6 Incorporation of logging sequence

The simulation of plausible logging scenarios essentially represents a problem of tracking a mosaic of forest ages through time. While simple in concept, the tracking of successive differences in yield response for a slowly growing forest of mixed ages that is subject to a mosaic of tree removal presents a rather complex task that requires careful computation.

In order to incorporate the required logging scenarios it was necessary to divide the forest area into 10,000 equal sized grid cells. This degree of discretisation was adopted for computational convenience and it has little physical significance. The net area of forest logged each year is typically around 1% - 2%, which requires the consideration of between 100 to 200 grid cells annually (the logging scenarios actually adopted for modelling are described in Section 4.3). The absolute area of each grid cell varies with the size of forest. For example for the smallest catchment considered (8 km^2) each grid cell represents an area of 0.08 ha; for the largest catchment of around 160 km^2, each grid cells represents an area of 1.6 ha.

Model runs were undertaken separately for both the harvestable and the non-harvestable areas. It was necessary to treat these areas separately in order to correctly account for the different age profiles of the forest through time; the reserved area of the forest is allowed to age uniformly through time, whereas the age of the harvestable area is dependent upon the logging scenario adopted.

Figure 5.D illustrates the (hypothetical) spatial distribution of tree age throughout the discretised forest. The model tracks the age of each of the 10,000 grid cells over the a period of simulation that may extend to 100 years. An illustration of the temporal variation of the forest age is provided in Figure 5.E, using the results obtained for the whole Karuah catchment. With this example, it seen that the proportion of old-growth forest gradually increases throughout the period of simulation, both as a result of leaving around 60% of the forest in reserve, and because the majority of logging activity involves the thinning of young trees, interspersed with the occasional selective logging of mature to old-growth timber. Once the temporal mosaic of tree age has been determined for each year of simulation, the impact of water yield is then assessed by use of the yield-response relationship as shown in Figure 5.C.

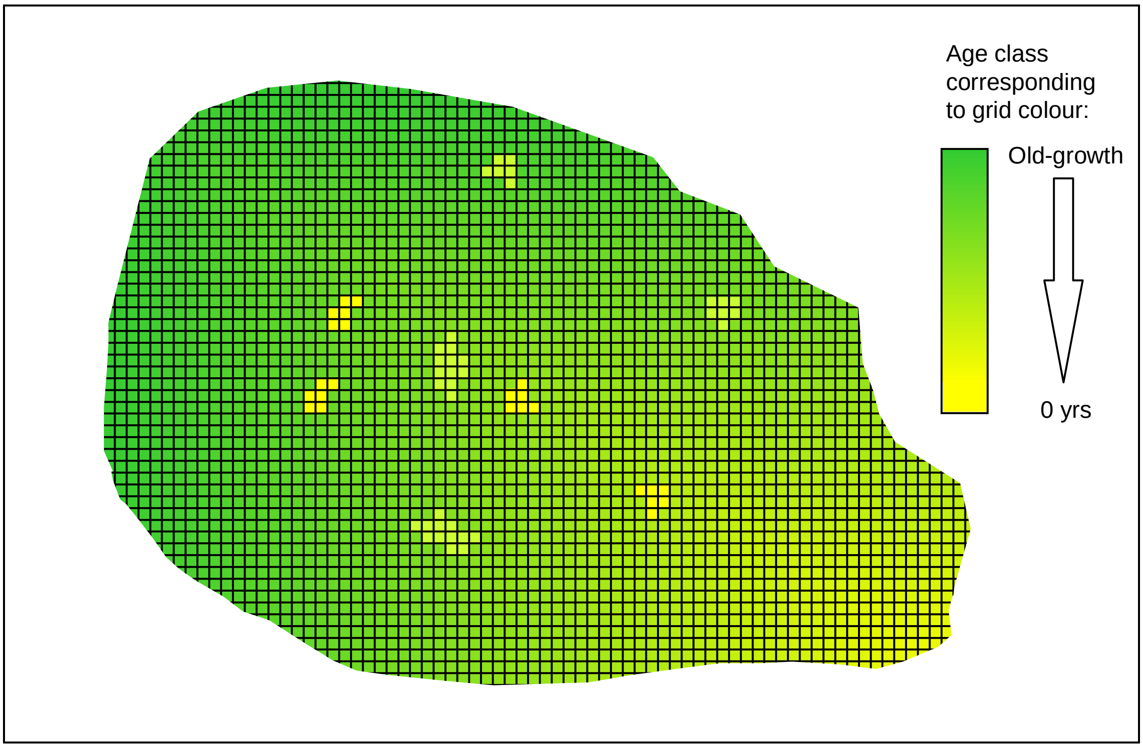

FIGURE 5.D SCHEMATIC ILLUSTRATION SHOWING THE SPATIAL DISTRIBUTION OF TREE AGE FOR A SINGLE YEAR OF SIMULATION

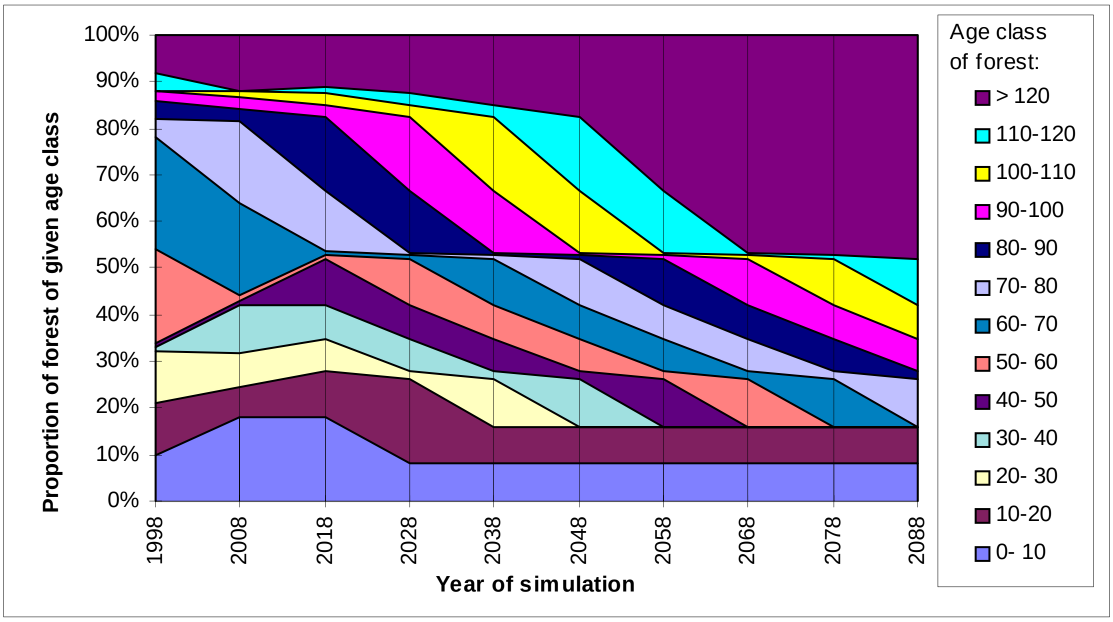

FIGURE 5.E TEMPORAL DISTRIBUTION OF TREE AGE FOR THE WHOLE FOREST AREA THROUGHOUT THE PERIOD OF SIMULATION (EXAMPLE SHOWN IS FOR THE KARUAH CATCHMENT, SEE FIGURE 5.K)

Simulation of the logging scenarios involves the following procedural steps:

1. The current age of the forest is specified by assigned an age to each grid cell based on a frequency distribution of age classes (adopted age profiles are discussed in Section 4.3.1)
2. The logging scenario is implemented by setting the age of any cells that are logged to zero, and incrementing the age of all other cells by one year annually.
3. Cells are selected for logging by sampling from a triangular distribution of age class corresponding to the nature of the selected activity. For example, if the logging scenario specifies that thinning removes trees of between 20 and 45 years of age, then the model selects cells only from this age range according to a triangular distribution. The process is schematically illustrated in Figure 5.F.
4. Finally, once the temporal mosaic of tree age has been determined for each year of simulation, the impact of water yield is then assessed by use of the yield-response relationship (Sections 5.2.3, 5.2.4 and 5.2.5).

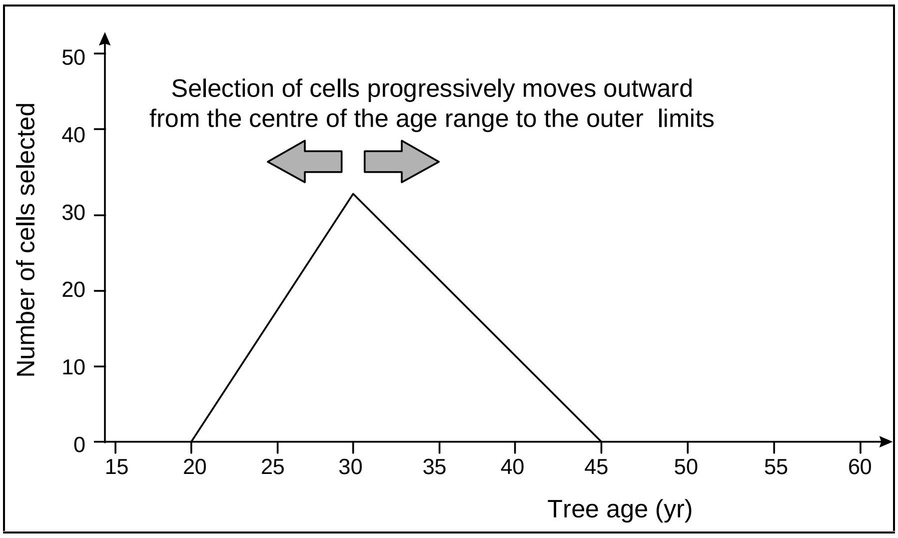

FIGURE 5.F SCHEMATIC ILLUSTRATION OF SELECTION OF GRID CELLS ON BASIS OF AGE CLASS

5.3 MODEL APPLICATION

From the foregoing, it is seen that the adopted modelling approach requires a range of both site-specific and regional inputs. The range of inputs and the manner in which they were derived for the study are summarised below:

- *Definition of catchment areas*. The areas of the forest that lie upstream of the stream gauging stations were derived using a GIS based on digitised catchment boundaries.
- *Regional yield-response curves*. Yield response curves corresponding to the clear-felling of old-growth forests were derived for two regions, as described in Section 5.2.2.
- *Mean annual rainfall*. Annual rainfalls were determined for each catchment by calculating the average of a rainfall field discretised to a grid-square resolution of 0.025°. This

rainfall field incorporates the influence of elevation as a spline surface and was fitted to observed data using elevation as an independent covariate.

- *Current forest age*. As discussed in Section 4.3.1, information on forest history for each State Forest was used to estimate the profile of forest age for the catchments of interest.
- *Plausible logging scenario*. Plausible logging scenarios were obtained from the relevant State Forest regional planning managers, as described in Section 4.3. The scenarios obtained for catchments located in the Lower North East and Southern Regions represent just one possible sequence of logging that could be adopted for the specific catchments identified. Site-specific scenarios could not be obtained for catchments located in the Upper North East region, and the scenarios were prepared on the basis of logging practices documented for other catchments elsewhere in the region.

5.4 COMMENTS ON THE ADOPTED MODELLING APPROACH

The adopted modelling approach to assessing the impact of logging on water yield is a substantial simplification of reality. No account is given to the complex interaction between climate, soils, vegetation, and topography, and the relationships are based on the results from a few sites which exhibit only a selected range of catchment characteristics. It is considered, however, that the adopted approach provides a reasonable "best guess" that is unlikely to be much improved even with the expenditure of considerable further effort.

The major barrier that prevents the derivation of more accurate estimates is simply the lack of information. This is a problem that cannot be overcome by simply increasing the degree of modelling sophistication. Information on yield changes over time is available for only a small number of catchments that reflect a narrow range of catchment behaviour. While it would be straightforward to develop and calibrate a range of conceptual models of varying complexity, the limited range of catchment characteristics would preclude the transposition of model parameters to other catchments. At best, transposition would need to be made using physically-based models whose parameters would need to be assigned on the basis of inference and speculation. However, our limited understanding of the complex interaction of the processes concerned, and the lack of suitable data even for such basic characteristics as terrain and soil depth (let alone information on such attributes as tree water use as a function of forest type, structure, senescence and climate) means that the uncertainty of such estimates would not be reduced.

While it is seen that one of the major problems faced in this area is the paucity of relevant information, there are a number of limitations of the adopted approach that could be improved upon. It is thus considered useful to classify the modelling limitations into two categories: those limitations that could be easily rectified with a modest amount of additional work, and those limitations that are not likely to be resolved even with the expenditure of considerable effort.

5.4.1 Limitations that could be improved upon with additional work

A number of limitations are the result of time constraints imposed on the project, and it is considered that the following issues could be readily resolved within perhaps a two month time frame:

- *Adopted logging scenarios*. There has been little coordinated effort to ensure that the adopted logging scenarios are consistent with future intended practice. The logging scenarios adopted must be regarded as little better than site-specific "best guesses" that could be made more precise with wider consultation and further effort. For the Upper North East, the adopted logging scenarios may be unreliable.
- *Current forest age*: The profile of existing forest age was estimated using information on historic activities which was prepared for the Mapping of Forest Management History Project for the CRA Process. Documentation was not available during the course of the study on the manner in which this information was used to derive the age profiles. The appropriateness of the method should be reviewed and assessed to determine whether any improvements in age estimates are possible. In addition, information on historic activities was not available for the Southern region.
- *Spatial aggregation*. At present the same initial age profile is adopted for both the harvestable and non-harvestable areas of the forest. It is possible that the areas of forest reserved from logging have a different age profile to that of the harvestable area, but at present the model was not configured to accept differing age profiles because the necessary information was not available within the timeframe of the project. The model could be modified to incorporate spatially explicit logging scenarios and variations in mean annual rainfall across the catchment. Given the crudity of the adopted yield-response curves it is uncertain whether spatially explicit outputs would reduce the uncertainty of the estimates, but the importance of this issue could be explored by some sensitivity analyses.
- *Sensitivity analyses*. It has not been possible in the time available to undertake sensitivity analyses to determine how the salient assumptions impact upon the results. The lack of information in this regard limits the manner in which the inputs and results can be interpreted. Such analyses would greatly facilitate the planning and scoping of future works aimed at the short-term resolution of this study's limitations and the longer term investment in research.
- *Stakeholder's inputs*. The yield modelling has raised some hydrologically complex issues that would benefit from discussion in a workshop forum. Only a limited number of experts have had input to the development of this methodology and a more detailed discussion of the issues amongst a wider group may facilitate further development and acceptance of future work.

5.4.2 Limitations that are unlikely to be resolved within the short term

Some limitations arise because our present understanding is limited, and it is considered that the following limitations are only likely to be resolved after the undertaking of long term research:

- *Yield-response relationship*. There is considerable uncertainty regarding the form of the yield response curve. While reasonably good information is available regarding the likely magnitude of yield increase immediately following disturbance, there is limited information regarding the maximum deficit, and no information at all regarding the nature and length of the yield-recovery period. Research programs based on field measurement and computer modelling are currently underway, and it is hoped that a better understanding of the processes involved will provide better predictions. It is unlikely that better information on yield response will be available in the short term.
- *Representativeness*. Results are only available for a very limited range of catchments. Changes in yield are the result of a complex interaction between climate, soils, vegetation and topography, and it is unlikely that the response characteristics from one catchment can

be directly transposed to another. At present our limited understanding limits the extent to which more detailed physical information can be incorporated. Rainfall is a crude surrogate for characterising regional differences, but it is unlikely that more sophisticated approaches will provide more precise results for some time.

- *Hydrologic regime*. The present study has only considered the impacts on annual yield. It is probable that different combinations of catchment characteristics would affect both the seasonality and frequency of low flows. While it is likely that information on a wide range of catchments will not be available for a very long time, physical reasoning could be used in combination with more detailed information on physical catchment characteristics to provide estimates of the impacts on seasonality and low flows. Considerable effort would be required to identify and collate the necessary physical information, and it is expected that the uncertainty of such estimates would be considerable.

5.5 RESULTS

5.5.1 Impact on forest yield

The impacts of the plausible logging scenarios on yield are first determined for the whole forest, where the results are expressed as a depth per unit area (mm) to facilitate comparison between different catchments.

Yield impacts are determined for the forest under:

- current conditions, ie the mixed-age profile of the forest as estimated for the year 1998; and,
- “old-growth” conditions, which assumes that the forest being logged is entirely at the senescent stage of water use.

For the case in which the impacts are determined for a forest of current age, the yield changes are reported for changes due to:

- *logging plus tree growth* - the total expected yield changes due to the logging of a growing forest compared to current conditions;
- *tree growth only* - the expected yield changes due to tree growth only, that is, for the “do nothing” scenario in which no logging is undertaken;
- *logging only* - the component of yield changes that are attributable solely to logging.

The last case effectively represents the differences in yield between the first two cases listed.

Time series plots corresponding to the above cases for the *gross forest area* are provided in Figure 5.G to Figure 5.M. The top two panels of each graph illustrate the impacts on yield for the forest under current and old-growth conditions, as discussed above. The changes in yield due to the logging of the current forest can be compared to current yields in the catchment, as well as to the yields that would be expected from an old-growth forest. These two comparisons merely reflect a difference in datum used to compare the changes, as illustrated by the schematic in Figure 5.C. The comparison based on current conditions is shown by the left-hand axis of the top panel, and the comparison based on old-growth conditions is shown by the right-hand axis.

In addition, the lower panel on each graph indicates how the average age of the forest is calculated to vary with time under the logging scenario adopted. Two curves are provided: one curve reflects the changes in average age for the harvestable area only, and the other reflects changes in average age for the whole forest. The initial average age shown at the beginning of the simulation period merely represents the arithmetic mean of the current estimated age of the forest, and changes through time are the result of the imposed logging regime on the forest, which is calculated to be the annual mean of the 10,000 grid cells used in the model.

In order to illustrate the above concepts, the following observations are made for the Eden catchment located in the Upper North East region (Figure 5.G):

- Changes in catchment yield due to both logging and tree growth are shown in the top panel by the thick solid line. With reference to the left-hand axis, it is seen changes in yield increase from zero (current conditions in 1998) to around 50 mm in the year 2020, then reduce to an increase of around 20 mm in the year 2045.
- If logging was not undertaken (see dashed line, top panel), catchment yield would increase monotonically to around 85 mm by the year 2055; with reference to the right hand axis, it is seen that this represents a yield that is around 10 - 15 mm less than what could be expected under old growth conditions.
- The thin solid line in the top panel illustrates the changes in yield that are solely attributable to logging. It is seen that, separate to the changes in yield associated with forest growth, logging results in a modest short term increase in yield, followed by an decrease of around 70 mm.
- If the logging scenario was applied to an old-growth forest (middle panel), it is seen that a short period of increasing yield is followed by a more sustained period of declining yield, to a maximum deficit (within the simulation period) of around 75 mm.
- With regard to the lower panel, it is seen that the current average age of the forest is around 75 years. As a result of logging, the average age of the whole forest increases by around 30 years over the 55-60 year period of simulation; the average age of the harvestable area of the forest fluctuates within around 5 years of the current age.

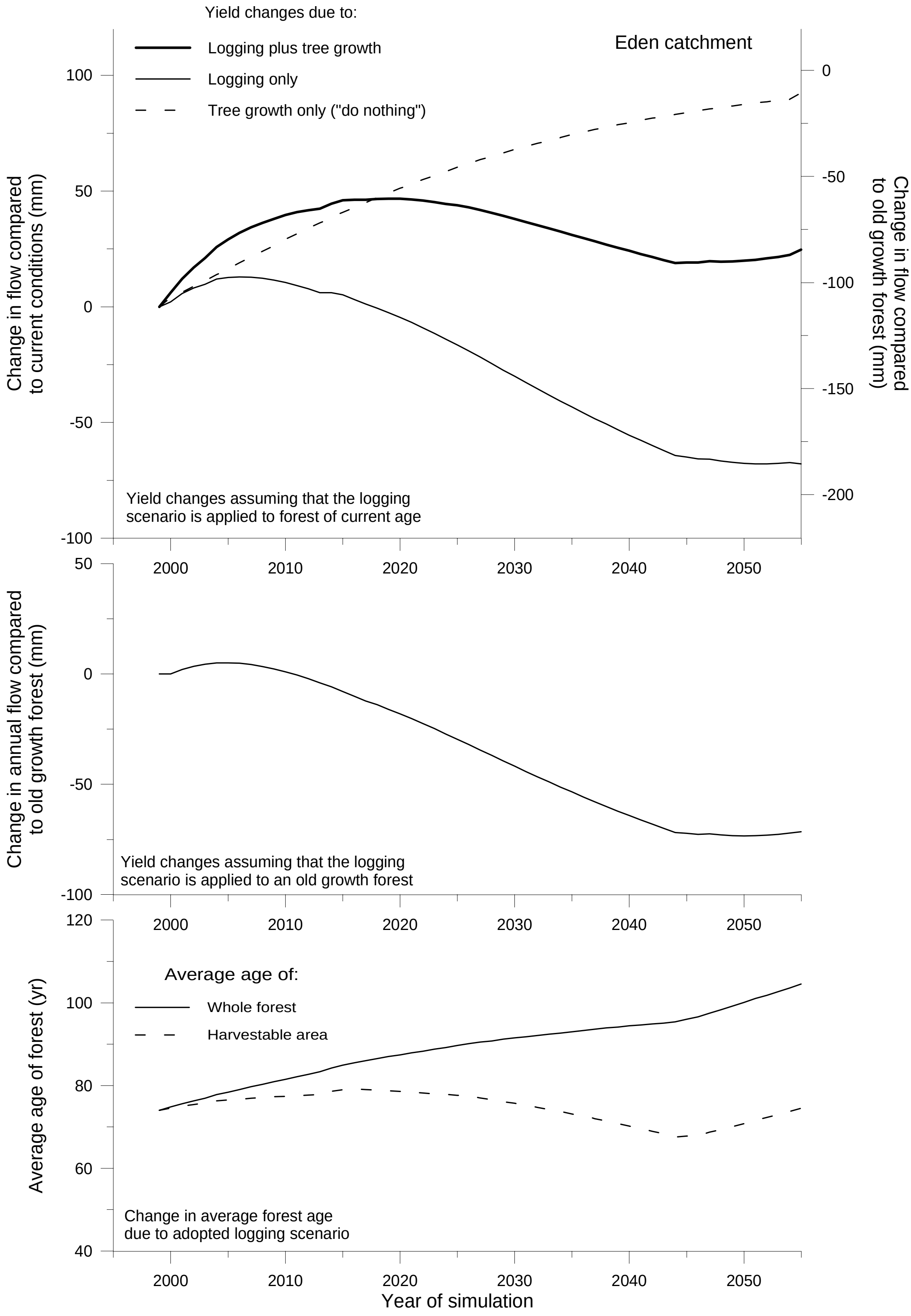

FIGURE 5.G THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE EDEN CK CATCHMENT, UPPER NORTH EAST REGION.

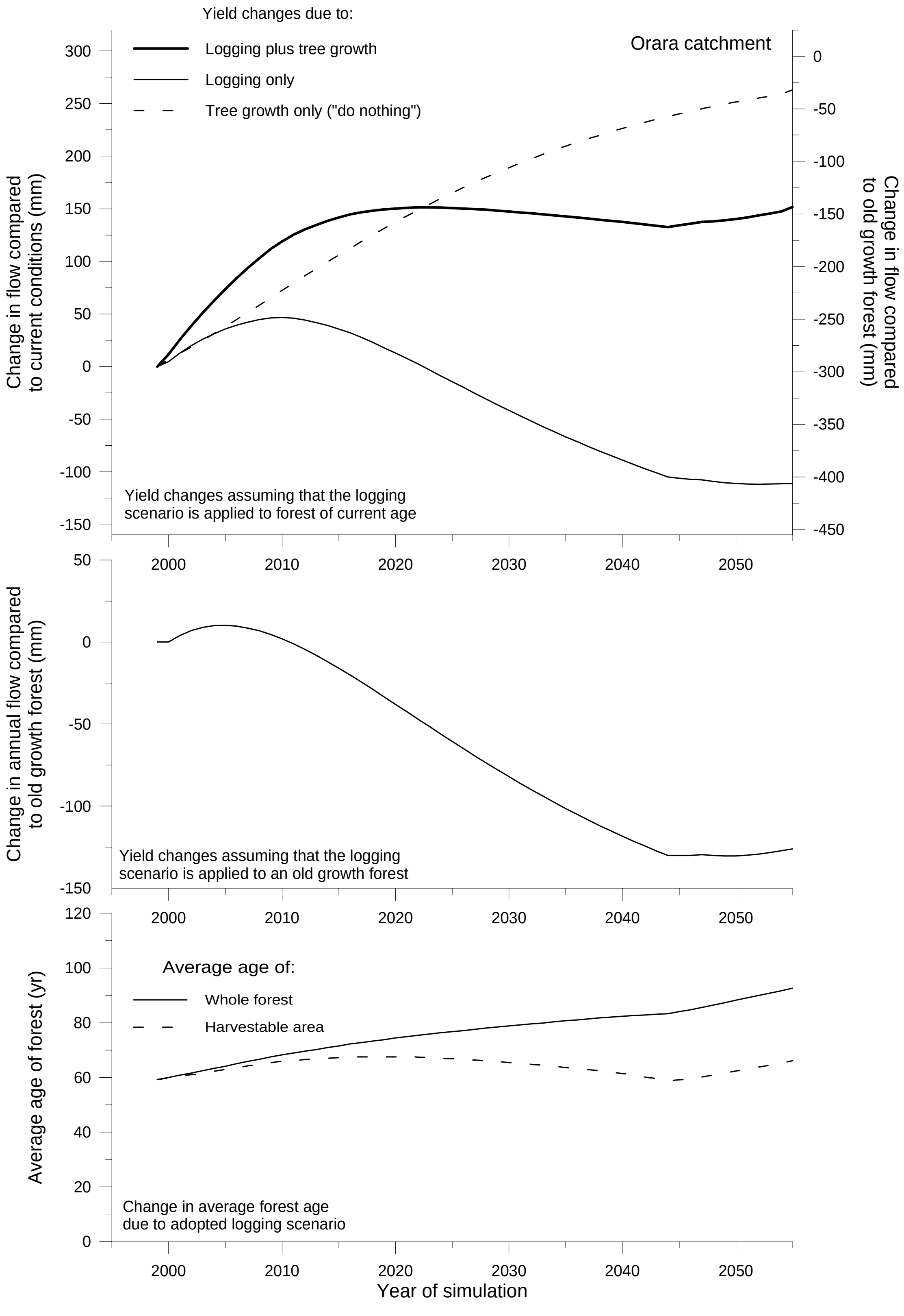

FIGURE 5.H THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE ORARA RIVER CATCHMENT, UPPER NORTH EAST REGION.

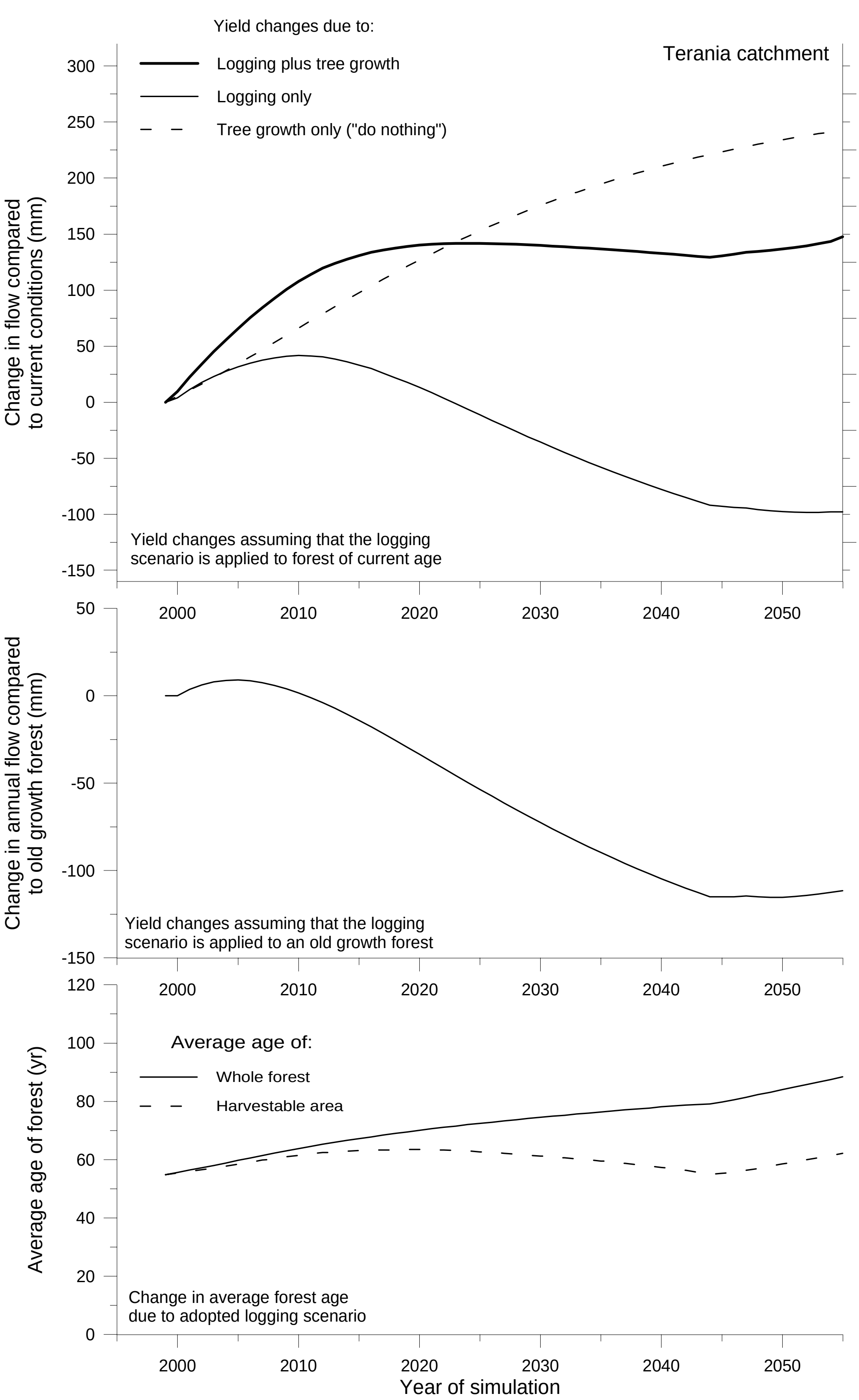

FIGURE 5.I THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE TERANIA RIVER CATCHMENT, UPPER NORTH EAST REGION.

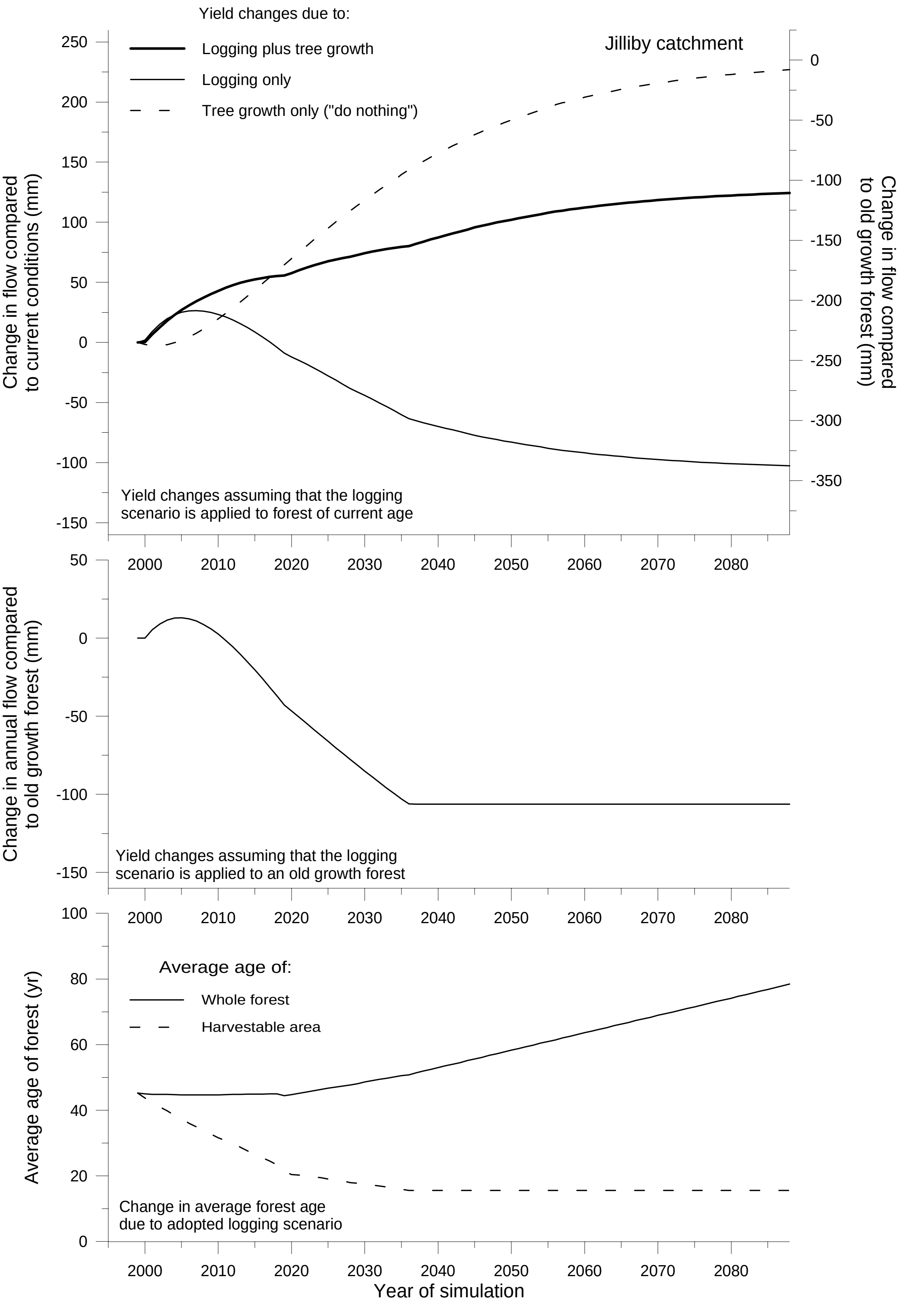

FIGURE 5.J THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE JILLIBY CREEK CATCHMENT, LOWER NORTH EAST REGION.

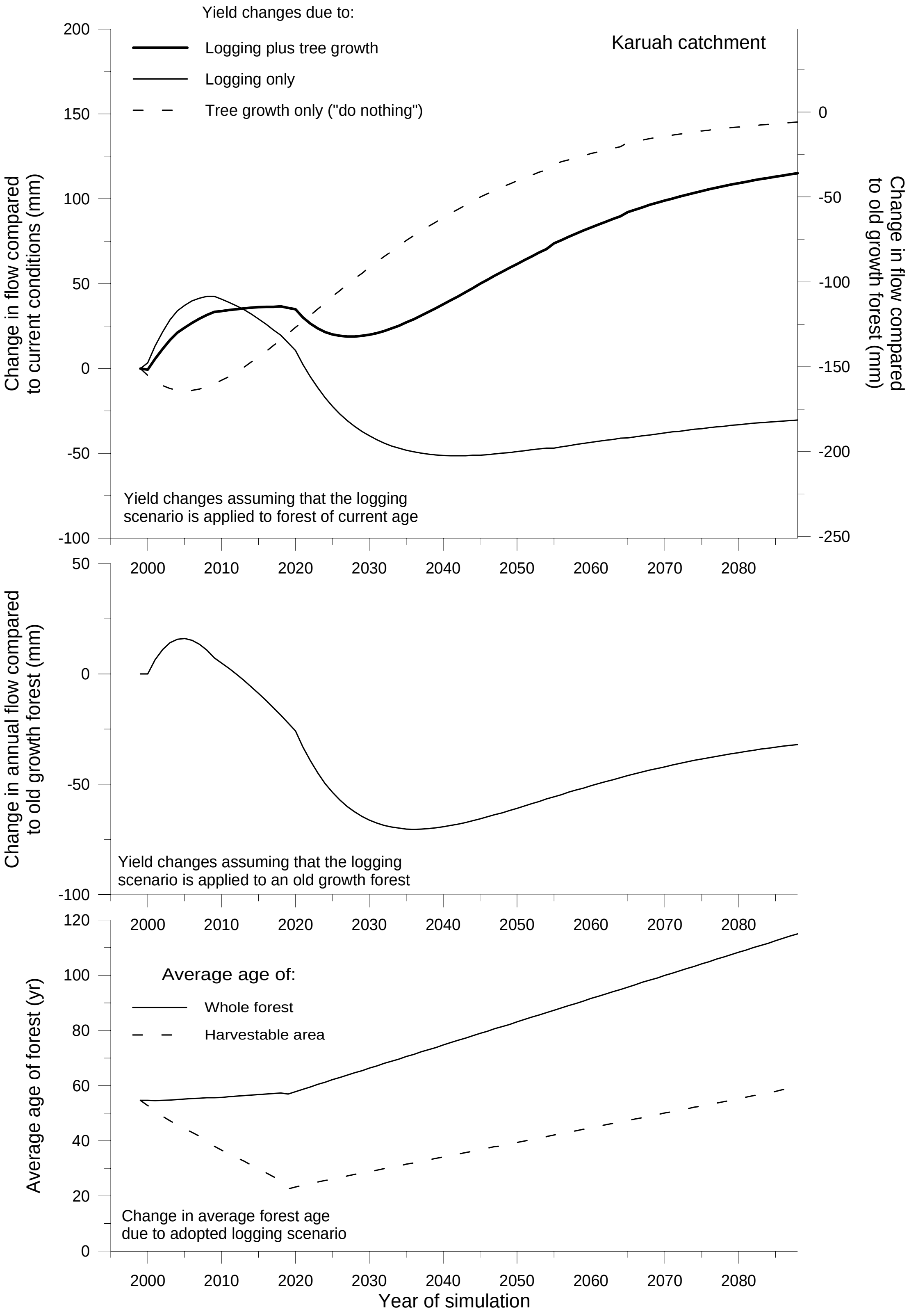

FIGURE 5.K THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE KARUAH RIVER CATCHMENT, LOWER NORTH EAST REGION.

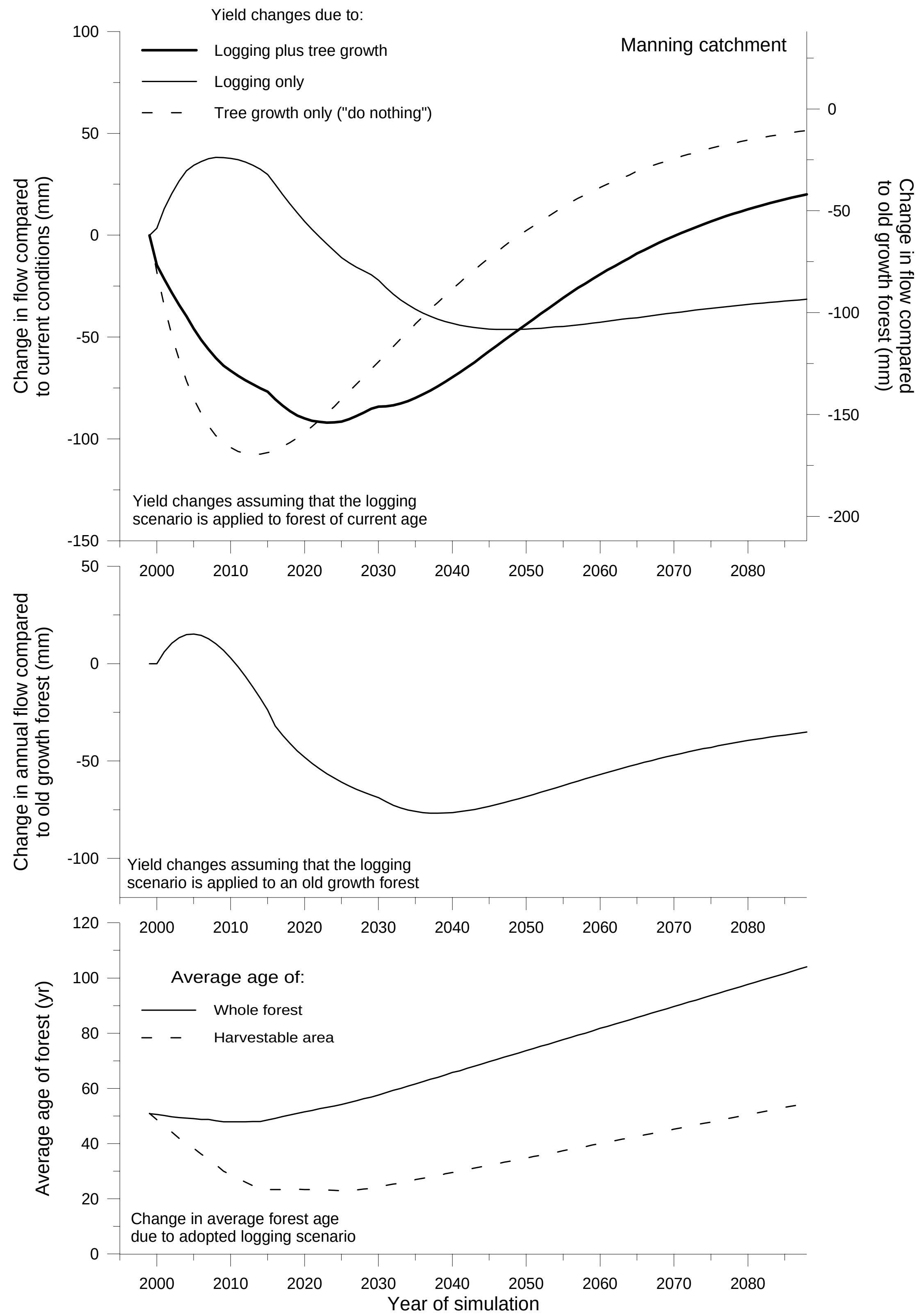

FIGURE 5.L THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE MANNING RIVER CATCHMENT, LOWER NORTH EAST REGION.

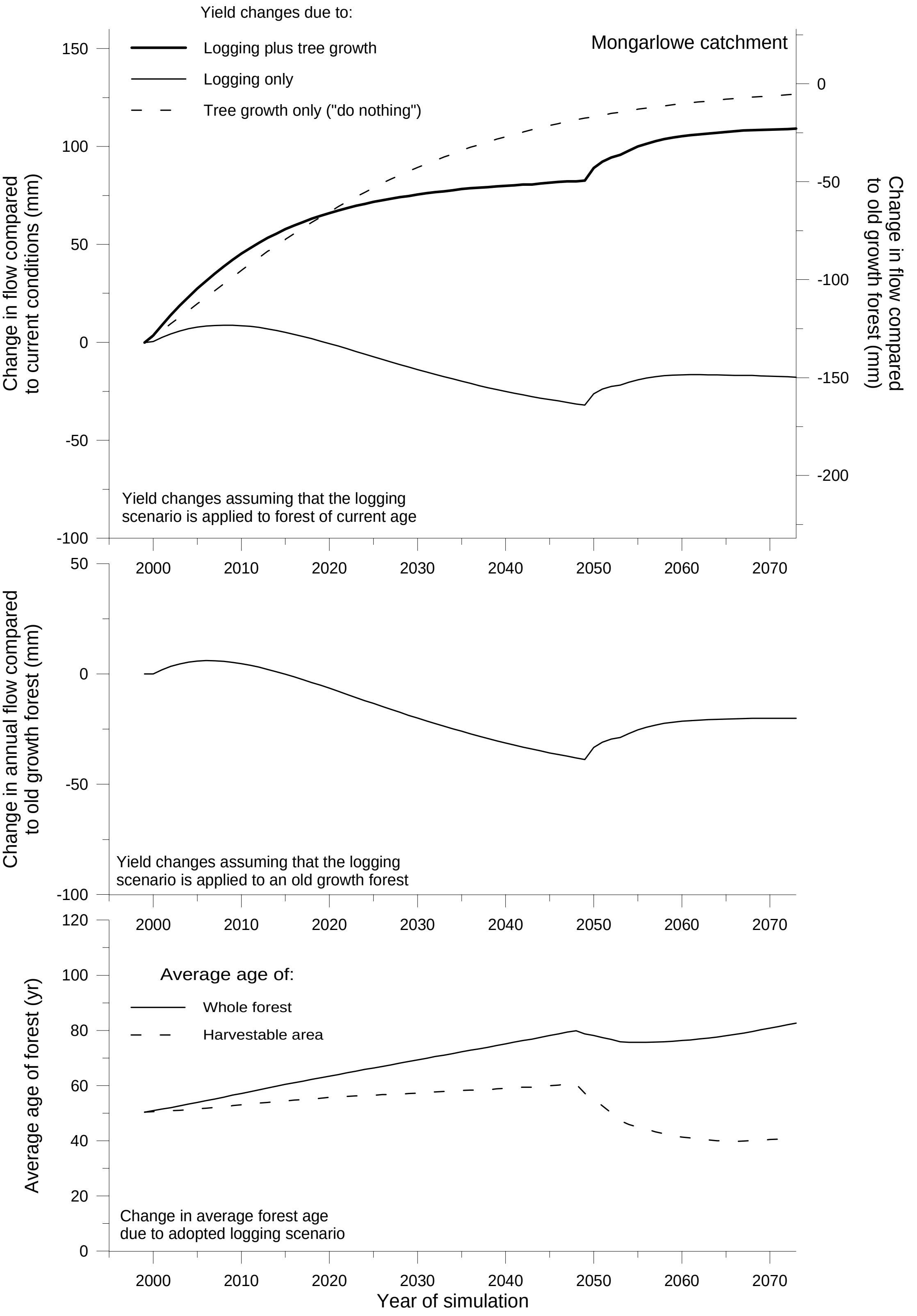

FIGURE 5.M THE IMPACT OF ONE POSSIBLE LOGGING SCENARIO ON FOREST YIELD IN THE MONGARLOWE RIVER CATCHMENT, SOUTHERN REGION.

5.5.2 Impacts on the Downstream Conditions

In the previous section the change in yield is expressed as a change in flow per unit area (in mm). This change was converted to a volume (in ML) by multiplying by the gross forest area so that it can be compared to the recorded flows at the two downstream streamflow gauges. The streamflow gauges used and the mean annual flows for these stations are summarised in Table 4.C.

In the Table 5.A the maximum increase and maximum decrease in yield are expressed as a percentage of the mean annual flow for the case of logging plus tree growth. When compared to flows immediately downstream of the forest, the largest increase in yield is calculated for the Jilliby catchment and is estimated to be over 60 percent of the mean annual flow. The minimum increase is for the Manning catchment where the change in yield is only 2 percent of the mean annual flow at the downstream gauge.

The changes are smaller at the gauge downstream of the mixed land use when expressed as a percentage of the mean annual flow because of the larger flows at the downstream gauge. The exception is the Orara catchment where the change is 8 percent downstream of the forest and 9 percent at downstream of the mixed land use, and this is a result of the large proportion of the catchment of the downstream gauge which is forested.

For the scenario of logging plus tree growth, no decrease in yield is estimated for any catchment except for the Manning catchment for which a maximum decrease of 9 percent is calculated (downstream of the forest).

TABLE 5.A YIELD CHANGES DUE TO LOGGING PLUS TREE GROWTH

Catchment	Downstream of Forest		Downstream of Mixed Land Use	
	Max Increase (%)	Max Decrease (%)	Max Increase (%)	Max Decrease (%)
Eden	5	0	3	0
Terania	15	0	4	0
Orara	8	0	9	0
Manning	2	-9	2	-8
Karuah	13	0	8	0
Jilliby	62	0	28	0
Mongarlowe	16	0	7	0

Table 5.B shows the changes in yield due to tree growth only and represents the “do nothing” scenarios. At downstream of the forest, the maximum increase in yield is approximately between 5 and 110 percent and the maximum decrease in yield is approximately between 0 and 10 percent. The changes for downstream of mixed land use are smaller when expressed as a percentage of the change in flow.

TABLE 5.B YIELD CHANGES DUE TO TREE GROWTH ONLY ("DO NOTHING SCENARIO")

Catchment	Downstream of Forest		Downstream of Mixed Land use	
	Max Increase (%)	Max Decrease (%)	Max Increase (%)	Max Decrease (%)
Eden	10	0	6	0
Terania	25	0	6	0
Orara	14	0	16	0
Manning	5	-11	5	-10
Karuah	16	-1	10	-1
Jilliby	110	-1	51	-1
Mongarlowe	19	0	8	0

Table 5.C shows the changes in yield due solely to the logging and represents the difference between the ‘logging plus tree growth’ and the ‘tree growth only’ scenarios. At downstream of the forest, the maximum increase in yield is up to approximately 10 percent and the maximum decrease in yield is approximately between 5 and 50 percent. The changes for downstream of mixed land use are smaller when expressed as a percentage of the change in flow.

TABLE 5.C YIELD CHANGES DUE TO LOGGING ONLY

Catchment	Downstream of Forest		Downstream of Mixed Land Use	
	Max Increase (%)	Max Decrease (%)	Max Increase (%)	Max Decrease (%)
Eden	1	-8	1	-5
Terania	4	-11	1	-3
Orara	2	-6	3	-7
Manning	4	-5	4	-4
Karuah	5	-6	3	-3
Jilliby	13	-51	6	-23
Mongarlowe	1	-5	1	-2

Comparison with Demands from Stressed Rivers Project

As part of the stressed rivers project described in Section 4.4 the monthly demands in ML and the 80th percentile flow (the flow exceeded 80 percent of the time) were estimated for the period from November to April inclusive (the most highly stressed period). The ratio of the demand to the 80th percentile flow for the most critical month was then used to assign the hydrologic stress. There is considerable uncertainty in the estimation of both the flow and the demand, however the ratio does provide a useful indicator of likely hydrologic stress.

The ratio of the demand to the 80th percentile flow for the subcatchments immediately downstream of the study areas is shown in the second column of Table 5.D. From this table it is clear that the lowest hydrologic stress has been calculated for the Manning catchment and the catchment under the highest degree of hydrologic stress is the Jilliby catchment.

In the last two columns the ratio of demand to the 80th percentile flow is presented for the case of the maximum yield increase and maximum yield decrease. The change in yield has only a very small effect on the calculated stress ratio.

In order to calculate the change in stress ratio it is simply assumed that the change in the 80th percentile monthly flow is the same as the change in the annual yield. It is possible that the changes in low flows are different to those obtained at the annual level, however as noted in Section 5.2.2 it has not been possible to quantity the effect on low flows.

TABLE 5.D RATIO OF DEMAND TO 80TH PERCENTILE FLOW FOR CRITICAL MONTH

Catchment	Hydrologic Stress Classification	Current Ratio (%)	Ratio corresponding to Maximum Yield Increase (%)	Ratio corresponding to Maximum Yield Decrease (%)
Eden	Low	36	35	36
Terania	Low	38	36	38
Upper Orara	Medium	42	38	42
Manning	Low	6	6	7
Karuah	Medium	34	32	34
Jilliby	High	430	340	430
Mongarlowe	Low	27	25	27

Note: Results are for "logging and tree growth"

5.5.3 Sensitivity Analysis

There are a number of inputs used in the study that are uncertain, and it is desirable to determine how these impact on the results. Unfortunately, time constraints only allowed the assessment of the impacts of selected initial age profile and logging scenario assumptions.

Initial Age Profile

Two different sources of information were made available during the course of the project on the initial age profile. One set of estimates was provided by the relevant Regional Planning Managers of State Forests; these estimates were based on judgement and local knowledge, and were considered "best guesses" only. The other set of estimates were provided by Greg Hall (pers. comm.), and were based on an analysis of forest history and structure. As discussed in Section 5.3, the latter set of estimates were adopted for the study as they were considered to be based on a more objective, and hence "testable" procedure.

In order to assess the nature of the sensitivity to the initial age profile, a simulation was undertaken using the two different sources of information. The differences in the initial age profiles used are illustrated in the bottom panel of Figure 5.N. From the variation in forest age over the period of simulation (central panel of the figure) it is seen that the average age of the adopted age profile is around 20 years younger than that provided by State Forests, but that the resulting pattern of changes through time are very similar. The top panel of the figure illustrates the expected changes through time arising from the different set of starting conditions. It is seen that the total impacts on yield due to both logging and growth are less for the adopted age profile than that provided by State Forests. Importantly, the impacts solely attributable to logging are more or less identical for both scenarios. This result arises because a similar age range of trees are logged regardless of the initial age profile.

The above analysis thus indicates that:

- the impacts attributable solely to logging are not sensitive to the initial age profile adopted; and,
- the total expected impact on yield due to both logging and growth will vary depending on the initial age profile adopted.

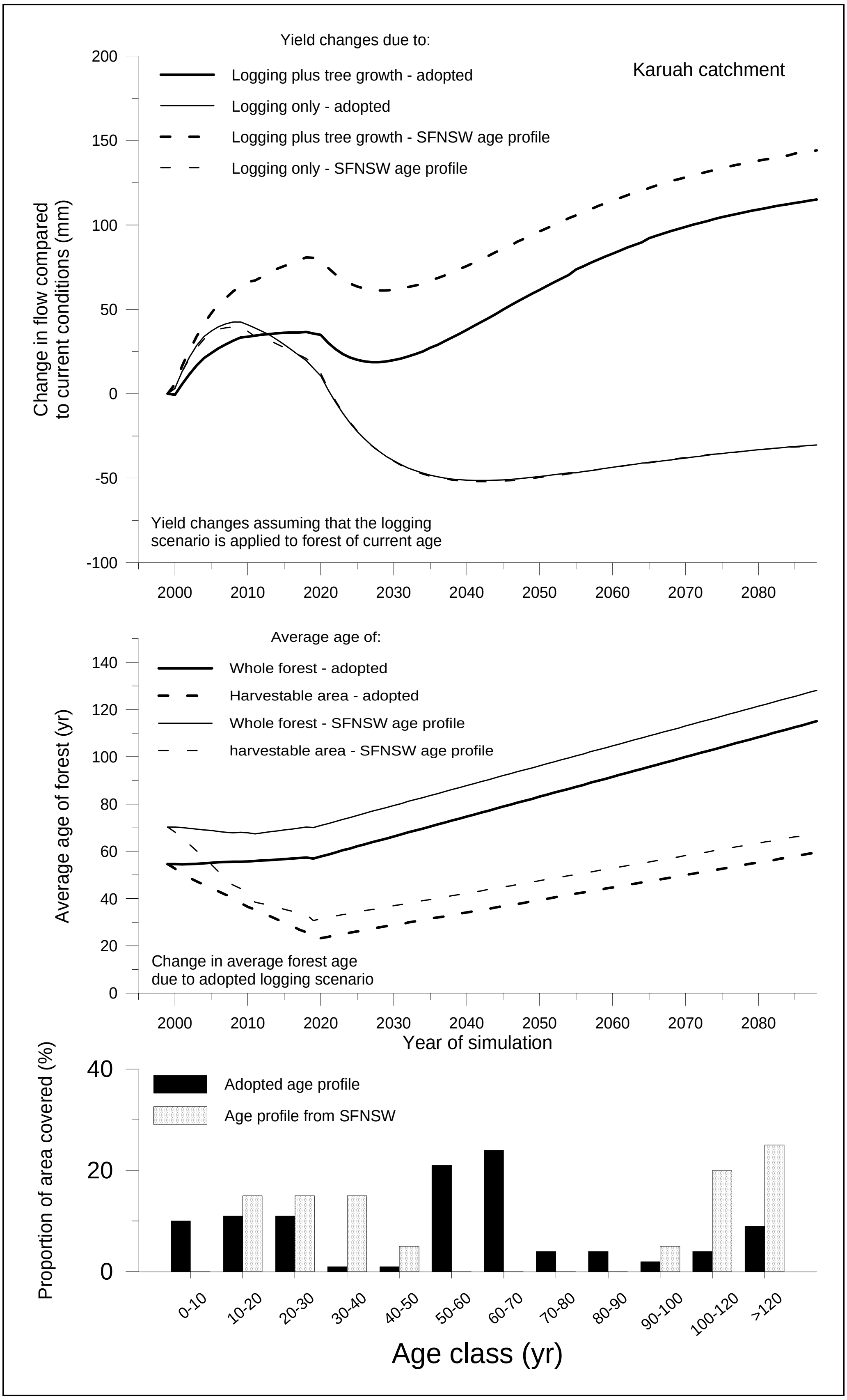

FIGURE 5.N SENSITIVITY OF RESULTS TO DIFFERENT INITIAL AGE PROFILE FOR THE KARUAH CATCHMENT

Logging Scenario

During the course of the study a “generic” logging scenario was provided that was considered to be applicable to many coastal forests (L. Orrego, North East Forest Alliance). The scenario is for selective logging and clear felling to occur simultaneously over a ten year period. Over this period the total canopy removal is 11% due to clear felling and the age of trees logged is uniformly distributed between 0 and 100 years. The total canopy removed due to selective logging is 11% with an nominal age of 50 years. This 10 year pattern is repeated over a 90 year period.

The sensitivity of the results to this alternative logging scenario is provided for the Terania Creek catchment in the Upper North East region, and the results are illustrated in Figure 5.O. It is seen that the overall yield response of the catchment under the two scenarios are similar, but the observed differences of around 50 mm may be significant when downstream conditions are considered. It is clear that the results are dependent on the logging scenario adopted, and thus in order to assess the likely upper and lower limits of the impacts it would be necessary to simulate an appropriate range of logging scenarios.

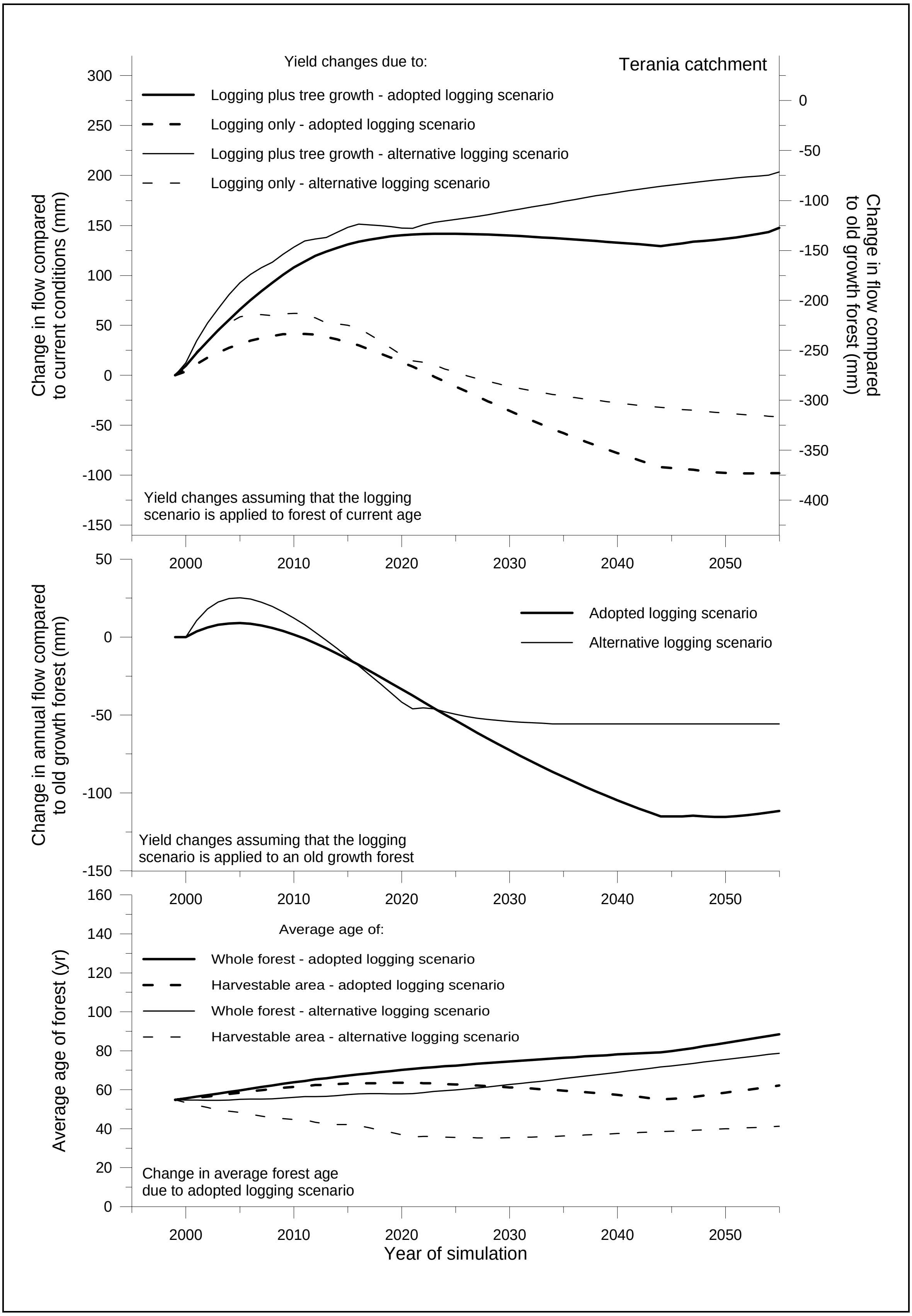

FIGURE 5.O SENSITIVITY OF RESULTS TO DIFFERENT LOGGING SCENARIO FOR THE TERANIA CATCHMENT

6. WATER QUALITY MODELLING

6.1 GENERAL OVERVIEW

Logging activities can impact on water quality in a number of ways, though the greatest impact (and hence focus of this study) is the increased level of suspended solids in streamflows. For the purposes of quantifying impacts, the main causes of disturbance that impact upon sediment production are divided into the following two components:

(i) logging activities within the general harvest and snig track area; and,
(ii) the maintenance, and use of permanent access roads.

The amount of sediment exported from logging operations within the general harvest area depends on many site-specific variables, including the level of soil disturbance, soil type, rainfall intensity, and the slope and length of passage to drainage lines. The amount of sediment generated by roading activities is also dependent upon a number of factors which are site-dependent, including unsealed road area and density, terrain steepness, the number of stream crossings, the length of road adjacent to streams, and the design of drainage outlet works.

The explicit consideration of all these factors is not possible within the time constraints of this project — indeed even detailed modelling estimates would be very speculative — and accordingly a methodology has been developed that attempts to take account of the salient influences in a robust and credible manner.

The overall approach may be summarised by the following steps:

1. Published and unpublished literature was obtained to derive probabilistic event-based sediment generation rates for both the general harvest and snig track area, as well as the permanent access roads.
2. Information on rainfall characteristics was obtained to convert the event-based rates to site-specific annual loads; for the general harvest and snig track area a relationship was also established to define the decline in sediment production as a function of time since disturbance, and separate generation rates were also provided for different classes of soil erodibility.
3. Spatial information on drainage lines, roads, soil erodibility, and forested catchment boundaries were imported into a Geographic Information System (GIS) and analysed to provide site-specific relationships for the proportion of the mobilised sediment that reaches the stream from both the general harvest and snig track area, as well as the permanent access roads.

4. The annual generation rates derived from Step 2 were combined with the site-specific delivery ratios from Step 3 to determine the annual sediment load reaching the drainage lines. The difference in sediment loads due to logging activities were then identified.

It is considered that the above methodology provides a robust and practical method of estimating sediment loads from the different catchments, and provides an objective basis for transposing the results obtained from published data to the specific sites of interest.

A detailed description of the above methodology is presented in the following sections.

6.2 GENERAL HARVEST AND SNIG TRACK AREA COMPONENT

6.2.1 Sediment load model

A detailed review of the literature has indicated that the amount of sediment reaching the stream can be estimated to be a function of rainfall erosivity, slope, soil regolith stability, distance from the stream, and time since logging. The first three environmental factors have been combined by State Forests into an “Inherent Hazard Category”, and this information is available as a GIS layer for all State Forest areas. Thus, the sediment load model can be largely simplified to be a function of Inherent Hazard Category, distance from the stream, and time since logging.

The approach adopted to estimate the amount of sediment load reaching the drainage lines is to determine the product of the annual load of sediment that is mobilised within the general harvest and snig track area (the production rate, P_H) and the fraction of the mobilised sediment that reaches the drainage line (the sediment delivery ratio, SDR). This can be stated simply as:

$$S_{coup} = P_H * SDR$$

where S_{coup} denotes the sediment stream load originating from the combined general harvest and snig track area. The generation rate is assumed to be a function of Inherent Hazard Category, time since logging and rainfall intensity, and the SDR is assumed to be a function of distance from the drainage line.

6.2.2 Sediment Production Function

The approach used in this study to determine the annual production rate (P_H) was to develop a relationship based on research results between rainfall intensity and sediment generation, and then to use information on rainfall characteristics to transpose the research results to the various sites of interest.

Information on the relationship between rainfall intensity and sediment generation were obtained from the research results provided by Croke *et al.* (1997; in press; submitted[a]), as shown by the symbols in Figure 6.A. The observed data were obtained using a rainfall simulator to generate runoff from both the general harvesting and snig track area. The sites had been subjected to an integrated harvesting operation with timber used for both sawlog and woodchip production, followed by a post-harvest burn. The timber had been extracted using a bulldozer or rubber-tired skidder to create snig tracks and for hauling to a log processing area. Cross banks were constructed at regular intervals on snig tracks to divert runoff upon completion of log extraction. Runoff and sediment samples were collected for a range of rainfall intensities over a 30 minute period, for sites ranging in age between a few months and five years since the post-harvest burn. All sites were assessed to fall within Level 2 of the Inherent Hazard Category classification system.

For this study, the following function was fitted to the observed data:

$$G_{H2} = (R-R_{Ht}).C.e^{-K.T}$$

where G_{H2} denotes the sediment yield (t/ha) from the combined general harvest and snig track area for landscapes falling within level 2 of the Inherent Hazard Category, R is rainfall intensity in mm/hr, and T is the time since logging disturbance in years. The remaining variables are parameters that require fitting, where R_{Ht} is the rainfall intensity threshold below which no sediment is generated from the combined general harvest and snig track area, K is a time decay constant, and C is a coefficient.

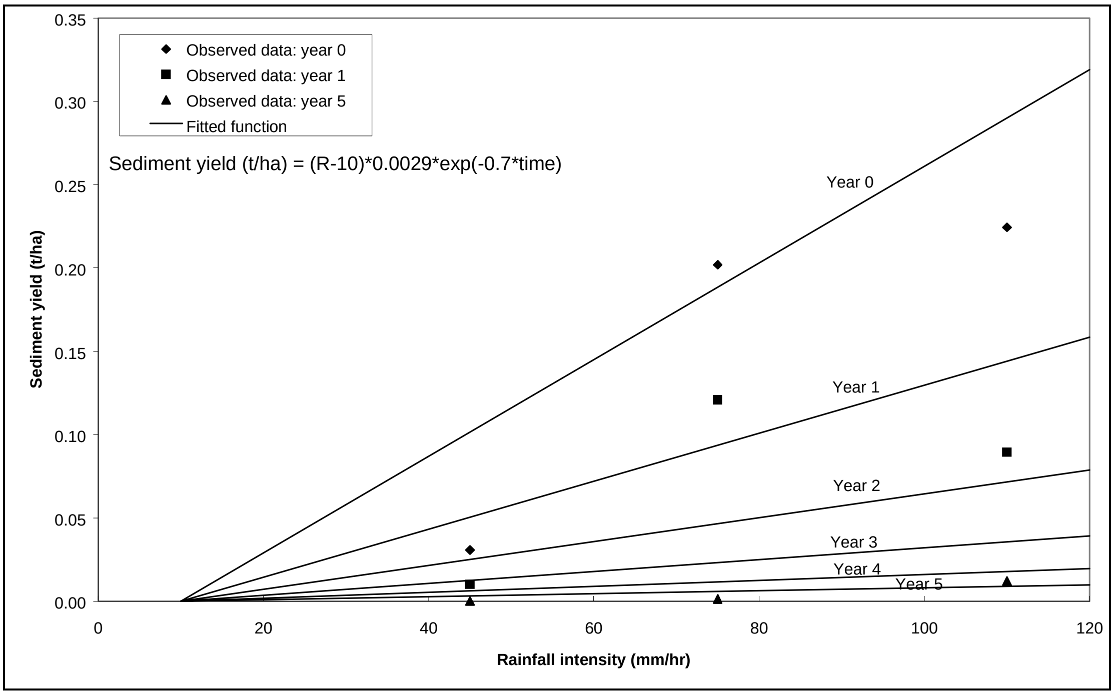

FIGURE 6.A THE ADOPTED RELATIONSHIP BETWEEN RAINFALL INTENSITY AND THE COMBINED GHA AND SNIG TRACK GENERATION RATE.

The three parameters were fitted to provide a reasonable, but conservatively high fit to the observed data, and the adopted relationship is shown in Figure 6.A. The adopted parameter values are as follows:

Rainfall intensity threshold, R_{Ht}	=	10 mm/hr
Time decay constant, K	=	0.7
Coefficient, C	=	0.0029

The parameters were fitted in a heuristic fashion as besides providing a reasonable fit to the observed data shown in Figure 6.A, it was also necessary to ensure that the adopted relationship provided annual generation rates that were consistent with the available evidence. The parameters C and K were determined solely from the event-based research data, and the parameter R_{Ht} was determined after incorporation of the rainfall characteristics used to convert the event-based generation rate (G_{H2}) into an annual rate (P_H). This conversion represents the transposition of the research results to the sites of interest, and provides a mechanism for incorporating site-specific differences in mean annual rainfall and rainfall intensities.

The conversion of an event-based generation rate to an annual yield is unfortunately not straightforward. The generation rates illustrated in Figure 6.A, are the result of 30 minute storms corresponding to annual exceedance probabilities (AEP) from around 1 in 2 to 1 in 100. Theoretically, to convert these values to an annual rate, it would be necessary to determine the expected frequency of occurrence of the full range of burst durations and intensities over an average year for the site of interest. In practice actual storm events are comprised of embedded bursts of overlapping durations, and thus it would be necessary to either explicitly account for the covariance structure of the rainfall bursts, or else derive a site-specific definition of storm event independence. Both these tasks present significant problems, and also require generation rates corresponding to a range of storm durations.

For this study, it was expediently assumed that the 30 minute rainfall burst represented a “critical duration” of storm that accounts for the majority of rainfall erosivity arising from embedded and overlapping events of different durations. This is not considered unreasonable, and is in fact analogous to the approach commonly adopted for flood estimation. It does however represent a simplification, and some empiricism (with respect to selection of the rainfall threshold, R_{Ht}) was required to ensure that the resulting rates was reasonable.

Annual sediment yields for each site were obtained from an analysis of rainfall characteristics based on pluviograph records and estimates of the long term mean annual rainfall. Long-term pluviograph records were extracted for representative locations within each of the Upper North East, Lower North East, and Southern regions. The pluviograph records extracted are listed in Table 6.A. For each set of pluviograph data, the frequency of occurrence of a range of rainfall frequencies was determined, and then used to estimate the annual rate of sediment production (in t/ha/yr).

TABLE 6.A REPRESENTATIVE PLUVIOGRAPH STATIONS ANALYSED.

Region	Station Number	Location	Period of Record
Upper North East	058099	Whiporie P.O.	1973-1987
Lower North East	061158	Glendon Brook	1966-1980
Southern	069062	Snowball	1974-1983

The estimation of the annual rate of sediment production is heavily dependent on the rainfall threshold (R_{Ht}) below which no sediment is generated. Research results obtained by Croke *et al.* (in press) indicate that the rainfall threshold below which no surface runoff was generated was 27 mm/hr. Adoption of this value for R_{Ht} yielded a negligible rate of sediment production, and thus the value of R_{Ht} was reduced to 10 mm/hr to provide generation rates consistent with the published literature. The adoption of a threshold value of 10 mm/hr is considered justifiable given the simplification of analysing the characteristics of a single burst duration.

The final estimates of annual sediment generation rate for the different sites is shown in Figure 6.B. These estimates were derived using the rainfall intensity characteristics derived for the representative pluviograph sites, factored to reflect the annual rainfall estimates for each catchment.

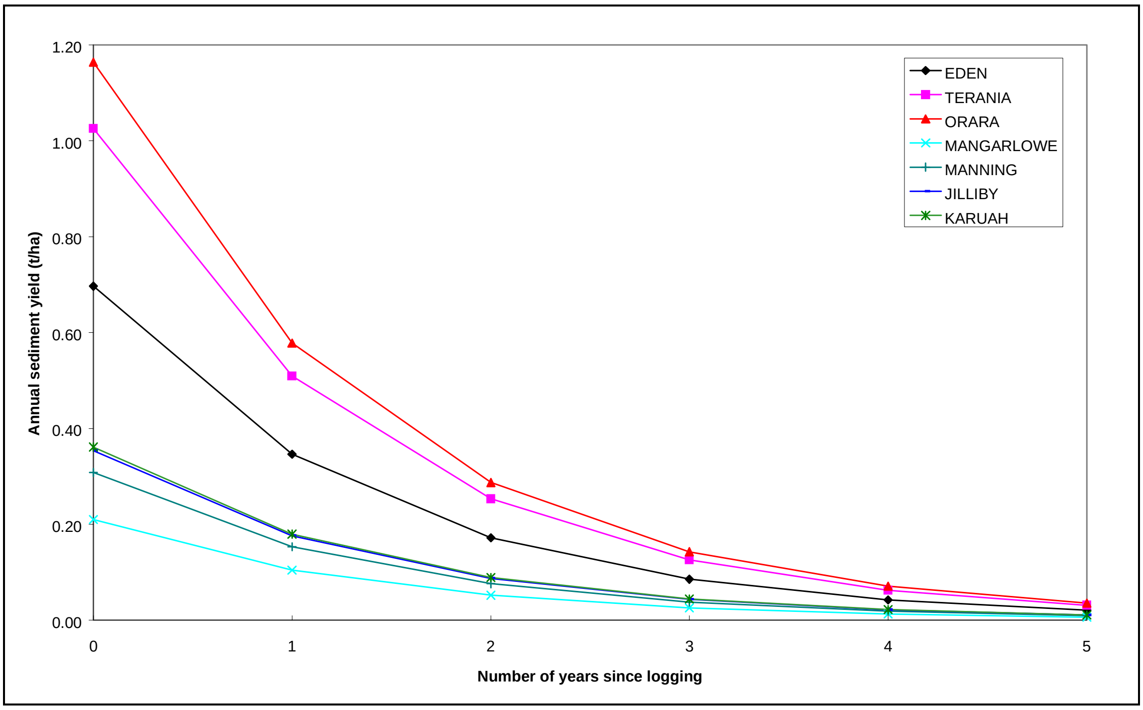

FIGURE 6.B SITE-SPECIFIC ANNUAL SEDIMENT YIELDS FOR THE COMBINED GENERAL HARVESTING AND SNIG TRACK AREA AS A FUNCTION OF TIME SINCE LOGGING (FOR LANDSCAPES THAT FALL WITHIN THE LEVEL 2 INHERENT HAZARD CATEGORY).

The last related issue that requires specification is the how the generation rates vary with Inherent Hazard Category (IHC). Unfortunately no appropriate research data is available for anything other than landscapes that fall into the 2nd level of the IHC, and accordingly any assessment of how rates vary with the different hazard categories is necessarily speculative. For the purposes of this study, it was assumed that rates of sediment yield from the different categories are as follows:

- level 1 of the IHC are 0.75 that of level 2, ie $G_{H1} = 0.75 * G_{H2}$
- level 3 of the IHC are twice that of level 2, ie $G_{H3} = 2.0 * G_{H2}$
- level 4 of the IHC is not considered as these areas are reserved from logging.

It must be stressed that there is no empirical evidence to support these factors, other than the fact that the resulting range of sediment production rates are within the range reported in the literature.

6.2.3 Catchment Sediment Delivery Ratio

The sediment delivery ratio (SDR) represents the fraction of mobilised sediment that reaches a drainage line. While a large amount of sediment may be mobilised during rainfall events, with appropriate management the majority of this sediment will be re-deposited prior to reaching a drainage line. The proportion of sediment that reaches drainage lines is dependent upon a complex interaction between overland flow distance, soil type, topography, degree of disturbance, and vegetation cover. In practice, however, the pathway length of the overland flow is the dominant factor, and in this study a single, lumped SDR is derived for the whole catchment and used as a surrogate for all other influences to predict the stream sediment load.

For a specific site, the SDR is easily calculated knowing the distance between the area of disturbance and the watercourse. The relationship used in this study is based on an exponential decay function, and is illustrated in Figure 6.C. This relationship is based on judgement, though clear support is provided by Novotny and Chester (1989) that pathway length is a major contributor to explaining SDR and the nature of the relationship is an exponential decline. The selection of the decay constant relies upon the judgement of the authors based on their experience.

It is assumed (Croke *et al.*, submitted[a]) that all the material entering this deposition phase is less than 63 microns in diameter; all sediment greater than 63 microns is assumed to be deposited within the first few metres after leaving the eroding surface. Deposition is through settling as a result of flow velocity reduction and reduction of the volume of overland flow through infiltration.

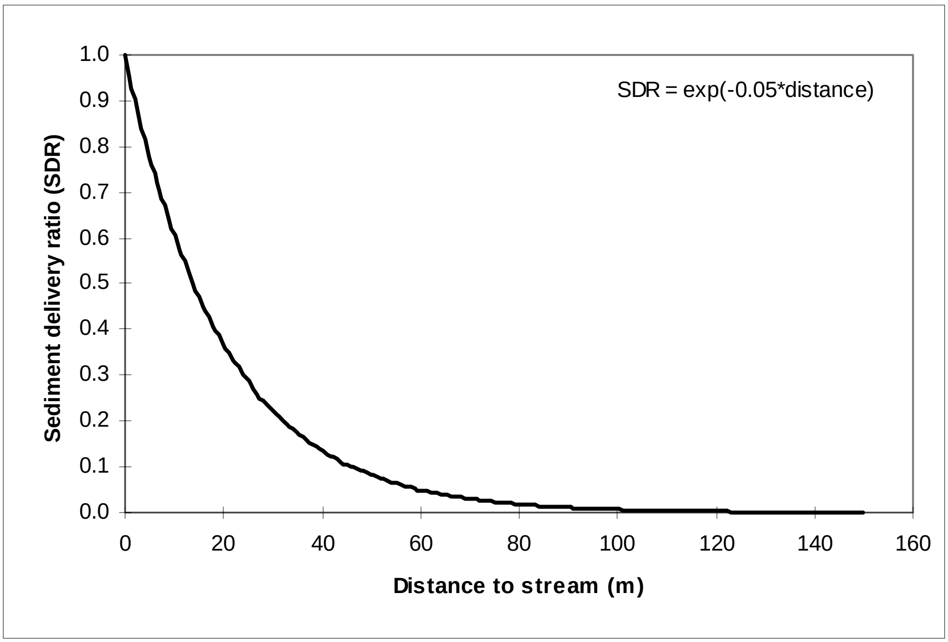

FIGURE 6.C RELATIONSHIP BETWEEN SEDIMENT DELIVERY RATIO AND DISTANCE FROM STREAM.

In order to derive an SDR value characteristic of a whole forest, it is necessary to derive an average pathway length that is based on the distance between all areas suitable for logging and the downstream watercourse. To this end, a GIS was used to analyse information specific to each catchment. The analyses were based on the following information:

- *Catchment drainage network* - the standard 1;25,000 scale information on drainage lines is not detailed enough to identify all the potential drainage lines within a catchment, and thus a “zeroth” order stream layer derived using a Digital Elevation Model was used (project PA4/2/2 undertaken by Tom Moore).
- *Areas suitable for logging* - these areas were defined to lie outside the buffer strip allowance prescribed by the EPA licence schedule, but only those areas classified as levels 1 to 3 of the Inherent Hazard Category were considered (level 4 is excluded from logging).

The above information on drainage lines, buffer allowances and Inherent Hazard Category was provided by State Forests in a digital form suited for analysis by a GIS. Once collated, the digital information was processed to determine the proportion of catchment falling within a succession of pathway distances from the drainage lines. An example of the information derived is shown in Figure 6.D for the Karuah catchment. It is seen from this figure that there is no fraction of the forest suited to logging that is within around 10 m from a drainage line. This distance represents the minimum buffer strip allowance provided by the EPA licence schedule. Although not clearly discerned from Figure 6.D, around 6% of the available area in the Karuah catchment is within 20 m of a drainage line, and 15% is within 30 m.

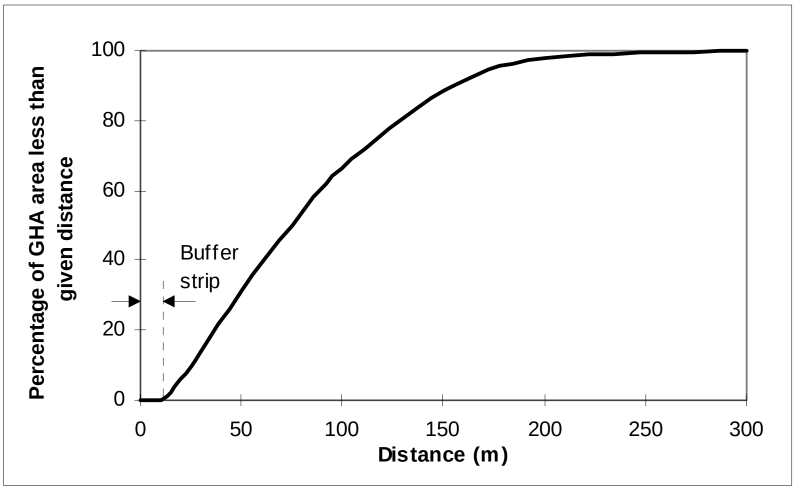

FIGURE 6.D RELATIONSHIP DEFINING THE PROPORTION OF THE AREA SUITABLE FOR LOGGING IN THE KARUAH CATCHMENT AS A FUNCTION OF THE DISTANCE FROM THE DRAINAGE LINES.

Catchment-specific information on the relationship between the SDR and pathway length, and the proportion of the catchment less than a given pathway length, is then convoluted to provide a density function that defines the relationship between proportion of the catchment less than a given SDR. The distances were measured direct as the DEM was too coarse to derive realistic flow path distances.

An example of the information derived for the Karuah catchment is shown in Figure 6.E. A characteristic value of SDR for the catchment was derived simply as the arithmetic mean of the derived density function; this value is shown for the Karuah example as a vertical line in Figure 6.E.

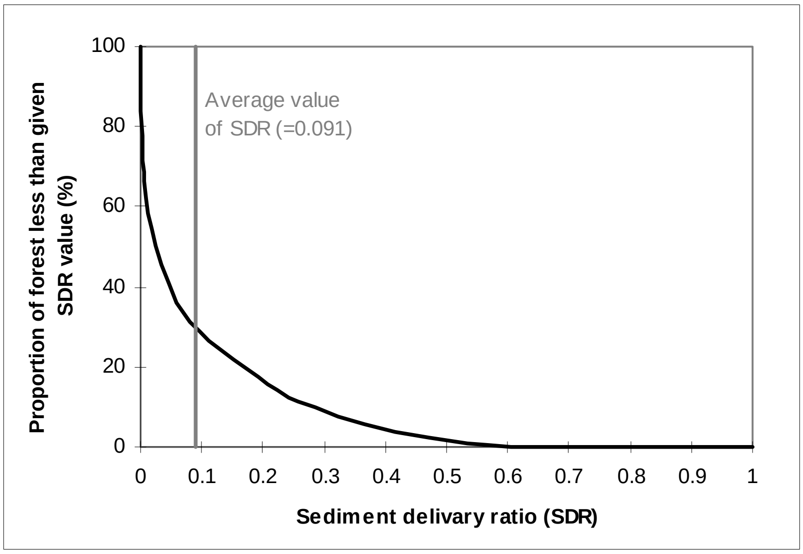

FIGURE 6.E RELATIONSHIP DEFINING THE PROPORTION OF THE AREA SUITABLE FOR LOGGING IN THE KARUAH CATCHMENT AS A FUNCTION OF THE SEDIMENT DELIVERY RATIO.

6.3 PERMANENT ROAD COMPONENT

6.3.1 Sediment load model

The approach used to estimate sediment production from roads is conceptually similar to that adopted for loads generated by the combined general harvest and snig track area. The dominant influence on the magnitude of sediment production is assumed to be the proximity of roads to the drainage lines. Thus, the basic approach to estimating the amount of sediment reaching the stream is to determine the product of the annual load of sediment that is mobilised within the road area (the production rate, P_R) and the fraction of the mobilised sediment that reaches the drainage line (the sediment delivery ratio, SDR). This can be stated simply as:

$$S_R \quad = \quad P_R * SDR$$

where S_R denotes the sediment stream load due to the roads.

6.3.2 Sediment Production Function

The overall approach used to determine the annual production rate (P_R) due to roads was the same as that adopted for the combined general harvest and snig track area. Research results were used to develop a relationship between rainfall intensity and sediment generation, and then information on rainfall characteristics was used to transpose the research results to the various sites of interest.

Information on the relationship between rainfall intensity and sediment generation from roads was obtained from the research results provided by Croke *et al.* (1997; unpublished; submitted^c), as shown by the symbols in Figure 6.F.

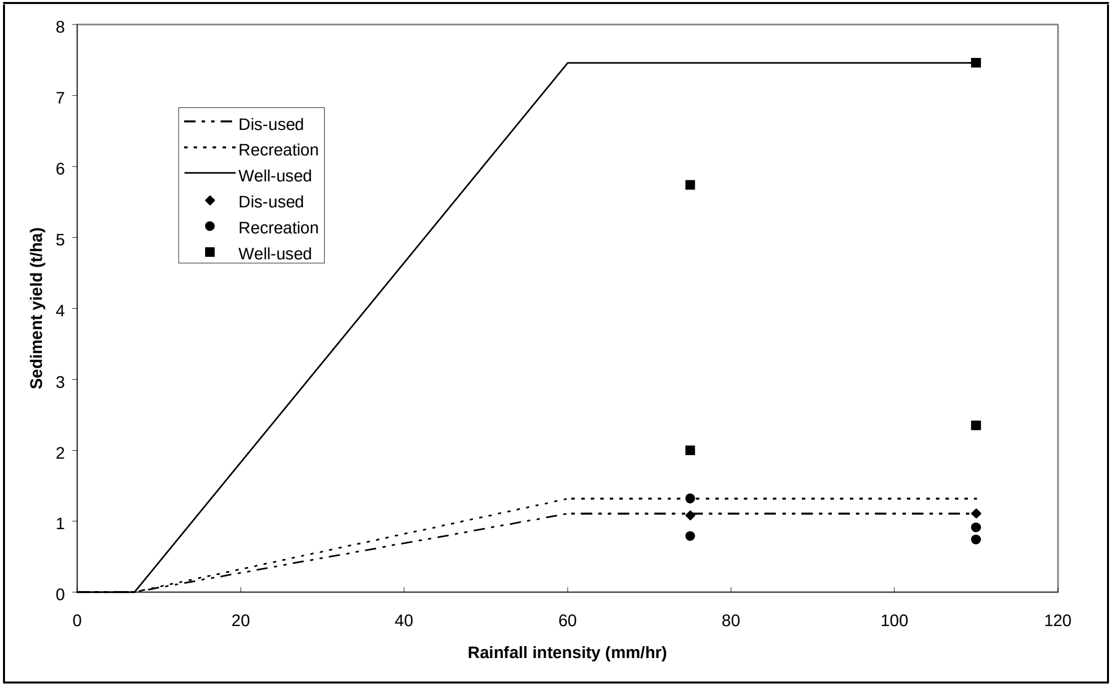

FIGURE 6.F THE ADOPTED RELATIONSHIP BETWEEN RAINFALL INTENSITY AND THE ROAD GENERATION RATE FOR VARIOUS CLASSES OF USE.

A function was fitted to the road generation rates using a similar heuristic approach as was adopted for the general harvest and snig track areas. The fitted function used to estimate sediment loads from the road differs in two respects to the approach adopted previously:

- estimated generation rates for the roads are assumed to be time-invariant (ie sediment loads are not assumed to decay exponentially with time since disturbance);
- the estimated generation rates are assumed to increase linearly with rainfall intensity up to an intensity of 60 mm/hr, and thereafter the generation rates are assumed to be constant.

The three parameter function between rainfall intensity and generation rates illustrated in Figure 6.F provides a reasonable, but conservatively high fit to the experimental data. It is arguable whether or not the data supports the adoption of anything more complex than a linear function, however the three parameter form was used to ensure that the annual sediment yields obtained were consistent with the range of values reported in the literature. Adoption of a linear function in combination with site-specific rainfall intensities yielded generation rates around half that expected, and thus the non-linear form illustrated in Figure 6.F was retained.

The event-based generation rates were converted to annual rates (P_R) using the same approach as adopted for the general harvest and snig track area. The rainfall characteristics were incorporated in exactly the same manner, the only difference being that the threshold rainfall intensity was set to 7 mm/hr. This lower value from roads is supported by research data collected by Croke *et al.* (unpublished).

The final estimates of annual sediment generation rate for different class of road usage within the different sites are shown in Figure 6.G.

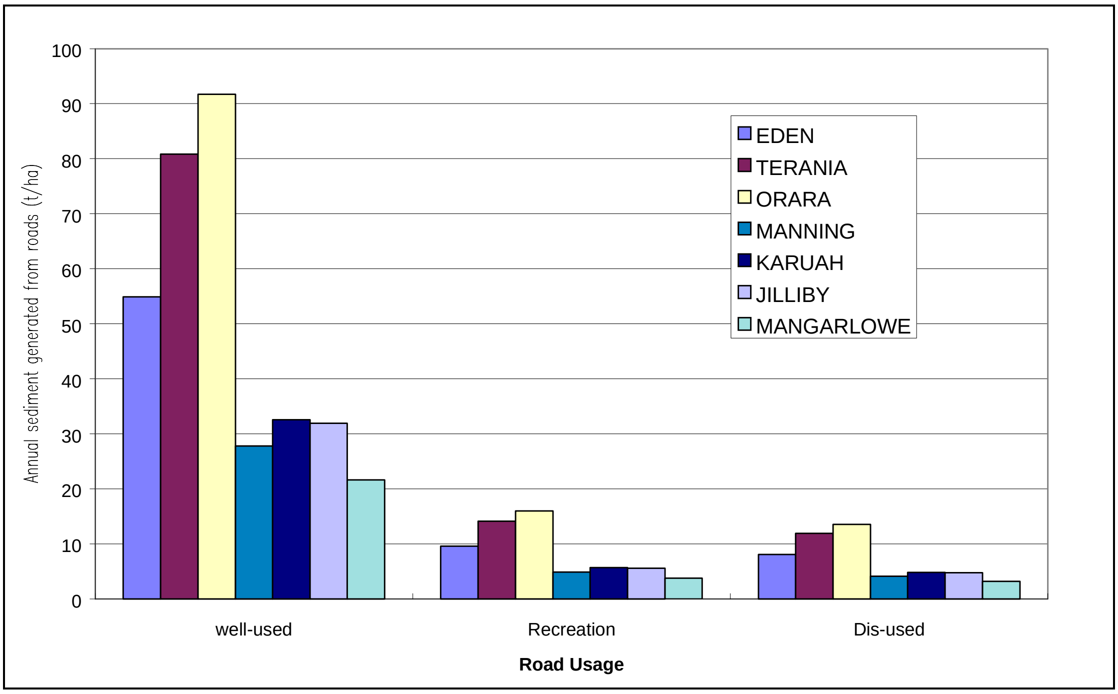

FIGURE 6.G SITE-SPECIFIC ANNUAL SEDIMENT YIELDS FOR ROADS IN DIFFERENT USAGE CATEGORIES.

6.3.3 Catchment Sediment Delivery Ratio

The overall approach used to determine the catchment-specific SDR is the same as that adopted for the combined general harvest and snig track area. The only difference between the two applications is that a GIS layer of the road network was analysed instead of the proportion of the catchment area suitable for logging. Also, since an existing road network was being analysed, there was no need to exclude buffer zones or areas classified as level 4 of the Inherent Hazard Category. Information on drainage lines was based on the standard 1:25,000 scale data, supplemented by the “zeroth” order streams provided by State Forests. The relationship used to relate SDR to the pathway distance between the road and the discharge line is as the same as that used for the general harvest and snig track area (Figure 6.C).

Once collated, the digital information was processed to determine the proportion of the road network falling within a succession of pathway distances from the drainage lines. An example of the information derived is shown in Figure 6.H for the Karuah catchment. It is seen that there is some proportion of the road network that lies within a few metres of the drainage lines, which is in contrast to the results obtained for the general harvest and snig track area (Figure 6.D). The difference between the two sets of results merely reflects the fact that roads cross drainage lines and that the existing network is not subject to a buffer strip allowance.

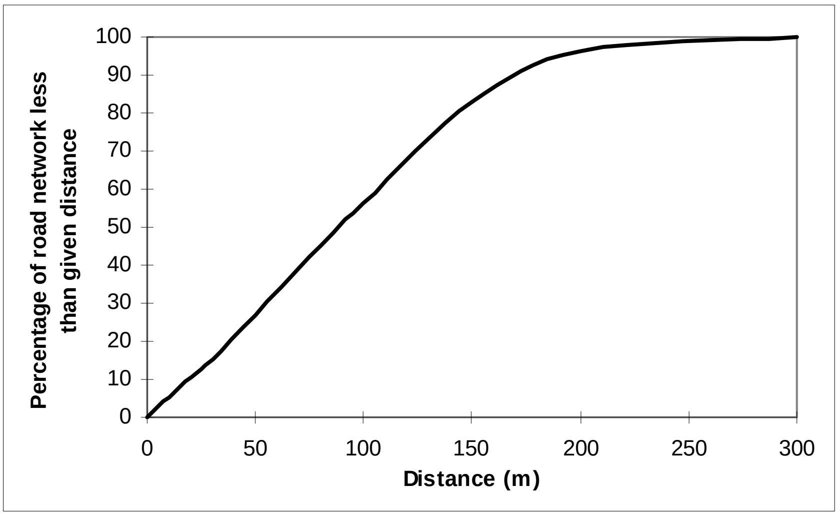

FIGURE 6.H RELATIONSHIP DEFINING THE PROPORTION OF THE ROAD NETWORK IN THE KARUAH CATCHMENT AS A FUNCTION OF THE DISTANCE FROM THE DRAINAGE LINES.

Catchment-specific information on the relationship between the SDR and pathway length, and the proportion of the catchment less than a given pathway length, was then convoluted to provide a density function that defines the relationship between proportion of the catchment less than a given SDR. An example of the information derived for the road network in the Karuah catchment is shown in Figure 6.I. A characteristic value of SDR for the catchment is derived simply as the arithmetic mean of the derived density function; this value is shown for the Karuah example as a vertical line in Figure 6.I.

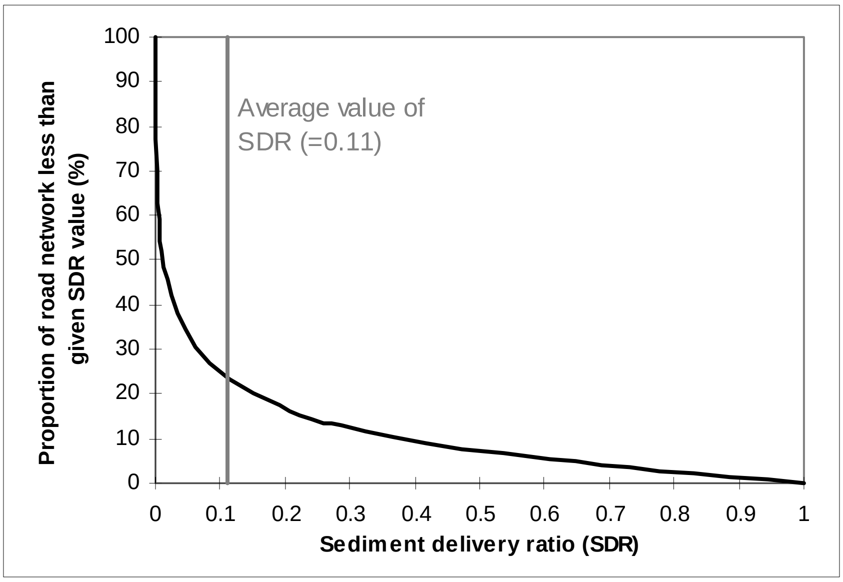

FIGURE 6.I RELATIONSHIP DEFINING THE PROPORTION OF THE ROAD NETWORK IN THE KARUAH CATCHMENT AS A FUNCTION OF THE SEDIMENT DELIVERY RATIO.

6.3.4 Estimation of Road Usage

As discussed in Section 6.3.2, different sediment generation rates have been estimated for the three categories of road usage: well-used, disused and recreation. Thus it was necessary to estimate the areas of roads subject to the different categories of usage within the state forests for both the no-logging and logging scenarios.

The different road classes within the forests were obtained from the GIS layer of roads obtained from State Forests NSW. Only the following classes of roads were found to occur in the study catchments:

- Class 3 - public roads, used by shire traffic and forestry operations;
- Class 4 - major forestry roads that are maintained;
- Class 5 - forestry roads that are not maintained; and,
- Class 6 - 4-wheel drive tracks (not maintained).

It was then necessary to estimate the percentage of the different road classes which fell within the 3 different categories of road usage. No data was available on the distribution of road usage within state forests and thus the values shown in Table 6.B were adopted after consultation with State Forests and are believed to be approximately representative of the likely distribution of road usage.

The largest change in road usage due to logging is considered to be for road classes 4 and 5 because most of road class 3 is already considered to be well-used and there is likely to be little increase for class 6 roads because they are only accessible by 4-wheel drive vehicles. For the case of 1% of the forest being logged the assumed changes in road usage are shown in Table 6.B.

In order to estimate the change in road usage for other logging scenarios, it was assumed that the change was proportional to the area being logged.

TABLE 6.B ASSUMED CHANGE IN ROAD USAGE DUE TO INCREASED TRAFFIC ASSOCIATED WITH LOGGING 1% OF THE FOREST AREA

Road	Width	No-logging			Logging			Change		
Class	(m)	well-used	disused	recreation	well-used	disused	recreation	well-used	disused	recreation
3	7.3	95%	0%	5%	97%	0%	3%	2%	0%	-2%
4	4.2	50%	30%	20%	60%	20%	20%	10%	-10%	0%
5	3.0	25%	65%	10%	30%	60%	10%	5%	-5%	0%
6	3.0	0%	95%	5%	5%	90%	5%	5%	-5%	0%

The typical road widths given in Table 6.B for the different road classes were used to estimate the area of forest roads within each catchment.

6.4 MODEL APPLICATION

From the foregoing, it is seen that the adopted modelling approach requires a range of both site-specific and regional inputs. The range of inputs and the manner in which they were derived for the study are summarised below:

- *Definition of catchment areas*. The areas of the forest that lie upstream of the stream gauging stations were derived using a GIS based on digitised catchment boundaries.
- *Generation rates*. The adopted generation rates for the general harvest and snig track areas are as detailed in Section 6.2.2, and those for the road network are as described in Section 6.3.2. The estimation of changes in road usage are as described in Section 6.3.4.
- *Derivation of catchment-specific Sediment Delivery Ratio(SDR)*. As described in Sections 6.2.3 and 6.3.3, the catchment SDR was derived using GIS information on the road network, drainage line network, buffer strip allowances, and the Inherent Hazard Category. The necessary GIS coverages were available for all catchments in the Upper North East and Lower North East regions, but not all required information was available for the Southern region. Accordingly, the catchment SDR value for the Mongarlowe catchment was calculated simply as the arithmetic mean of the values obtained from the other catchments.
- *Plausible logging scenario*. Plausible logging scenarios were obtained from the relevant State Forest regional planning managers, as described in Section 4.3. The scenarios obtained for catchments located in the Lower North East and Southern Regions represent just one possible sequence of logging that could be adopted for the specific catchments identified. Site-specific scenarios could not be obtained for catchments located in the Upper North East region, and the scenarios were prepared on the basis of logging practices documented for other catchments elsewhere in the region.

6.5 COMMENTS ON THE ADOPTED MODELLING APPROACH

The limitations of the adopted modelling approach to assessing the impact of logging on water quantity are generically similar to the water yield issues discussed in Section 5.4. As with the yield modelling, it has been necessary to adopt a “systems” approach in which only the modelling inputs and outputs have any physical significance; the form and parameterisation of the transfer functions used to convert model inputs into outputs are largely based on empirical evidence, and they do not incorporate the formulation or solution of any equations that govern physical processes.

As with the yield modelling, the adopted water quality modelling approach is a substantial simplification of reality. Little account is given to the complex interaction that exists between topography, soils, ground cover, degree of disturbance, rainfall duration and intensity, and the relationships are based on the results from a few sites which exhibit only a selected range of physical characteristics. In addition, the influence of scale has been largely ignored as it was necessary to derive catchment-scale predictions on the basis of plot-scale experiments.

While the modelling approach is simple, the degree of complexity adopted is commensurate with the nature of the available data. It is considered that the adopted approach provides a reasonable “best guess” that is unlikely to be much improved even with the expenditure of considerable effort. The strength of the adopted approach is that it attempts to combine the results of the most recent experimental work with site-specific characteristics of the study catchments. In particular, the ability of the model to accommodate differences in road network and drainage densities, and the incorporation of buffer strip and the Inherent Hazard Category is considered to provide more defensible predictions than that possible using regional estimates based on derivatives of the Universal Soil Loss Equation. There are a range of more physically-based models that could perhaps be used, but as with yield modelling, such models would require information on catchment characteristics that are not available, and the parameters would need to be assigned on the basis of inference and speculation.

While it is seen that one of the major problems faced in this area is the paucity of relevant information, there are a number of limitations of the adopted approach that could be improved upon. In a similar manner to that used with the yield modelling, it is considered useful to classify the modelling limitations into two categories: those limitations that could be easily rectified with a modest amount of additional work, and those limitations that are not likely to be resolved even with the expenditure of considerable effort.

6.5.1 Limitations that could be improved upon with additional work

A number of limitations are the result of time constraints imposed on the project, and it is considered that the following issues could be readily resolved within perhaps a two month time frame:

- *Drainage network*. The drainage network used is based on 1:25,000 scale information supplemented by estimates of “zeroth” order streams. It is understood that the “zeroth” order streams were derived from the analysis of a 1:25,000 scale Digital Elevation Model, and thus must involve considerable assumptions and uncertainty. Certainly a visual assessment of the derived drainage layer indicates a network that in many areas is inconsistent with the dendritic structure expected. It would be desirable to compare the 1:25,000 scale drainage density information with that obtained for a forested catchment, and to assess whether the estimated “zeroth” order streams are realistic. Attempts to obtain the necessary information within the time-frames of the project were unfortunately fruitless, though a range of different research and government agencies were contacted.
- *Discrimination of road class for derivation of SDR values*. At present the modelling is based on the derivation of a single catchment-specific SDR value for the whole road network, and no account is given to deriving separate relationships for the different road classes. The different classes of roads are assumed to have different use profiles under the

logging scenario, and thus the incorporation of separate SDR relationships for the different road classes would improve the estimation.

- *Rainfall characteristics*. Only a small number of pluviograph stations were used in the study, and it may be that longer records exist for stations that are more relevant to the sites of interest.
- *Spatial resolution*. The sediment loads were estimated assuming that the physical characteristics of the areas suitable for logging were the same as for those areas reserved from logging (except of course for exclusion of buffer strips and level 4 Inherent Hazard Category). There may be benefit to separately extracting SDR characteristics for those areas within the forest that are suited to logging.
- *Sensitivity analyses*. It has not been possible in the time available to undertake sensitivity analyses to determine how the salient assumptions impact upon the results. The lack of information in this regard limits the manner in which the inputs and results can be interpreted. Such information would greatly facilitate the planning and scoping of future works aimed at the short-term resolution of this study’s limitations and the longer term investment in research.
- *Stakeholder’s inputs*. The water quality modelling has raised some complex issues that would benefit from discussion in a workshop forum. Only a limited number of experts have had input to the development of this methodology and a more detailed discussion of the issues amongst a wider group may facilitate further development and acceptance of future work.

6.5.2 Limitations that are unlikely to be resolved within the short term

Some limitations arise because our present understanding is limited, and it is considered that the following limitations are only likely to be resolved after the undertaking of further research:

- *Conversion from event-based generation rates to annual yields*. The conversion of event-based generation rates to annual yields is based on the assumption of a single critical duration and the use of rainfall intensities with annual exceedance probabilities between 1 in 10 to 1 in 100. To improve this procedure it would be necessary to obtain information on sediment rates arising from bursts of different durations and more frequent intensities. This information can only be obtained from the results of detailed experimental work in the field.
- *Generation rates*. The rates adopted in this study are based on plot-scale measurements for a limited range of catchment and road conditions. The availability of results for a greater range of soil types and catchment conditions at larger scales would greatly improve confidence in the estimates.
- *Sediment Delivery Ratio*. At present SDR is estimated to be solely a function of path length to the drainage line. In reality this ratio is dependent on other physical characteristics such as slope, soil type, and nature of disturbance. Also, at present little real account is made for the likelihood of re-deposition of sediment once it has reached the drainage network. Appropriate information that would enable quantification of these factors is unlikely to be available in the short-term.

6.6 RESULTS

The impacts of the plausible logging scenarios on water quality are first determined for the whole forest, where the results are expressed as an annual load per hectare to facilitate comparison between different catchments.

The calculated sediment loads from the *gross forest area* for the various logging scenarios are shown in Figure 6.J. The different contributions to the total load are:

- current load from roads (no logging) which represents the constant supply of sediment from the road network with existing usage;
- additional contribution from roads due to the increased traffic which results from logging;
- contribution from general harvest and snig track area.

It is clear from Figure 6.J that the majority of the sediment load for the logging scenario is coming from the existing road network.

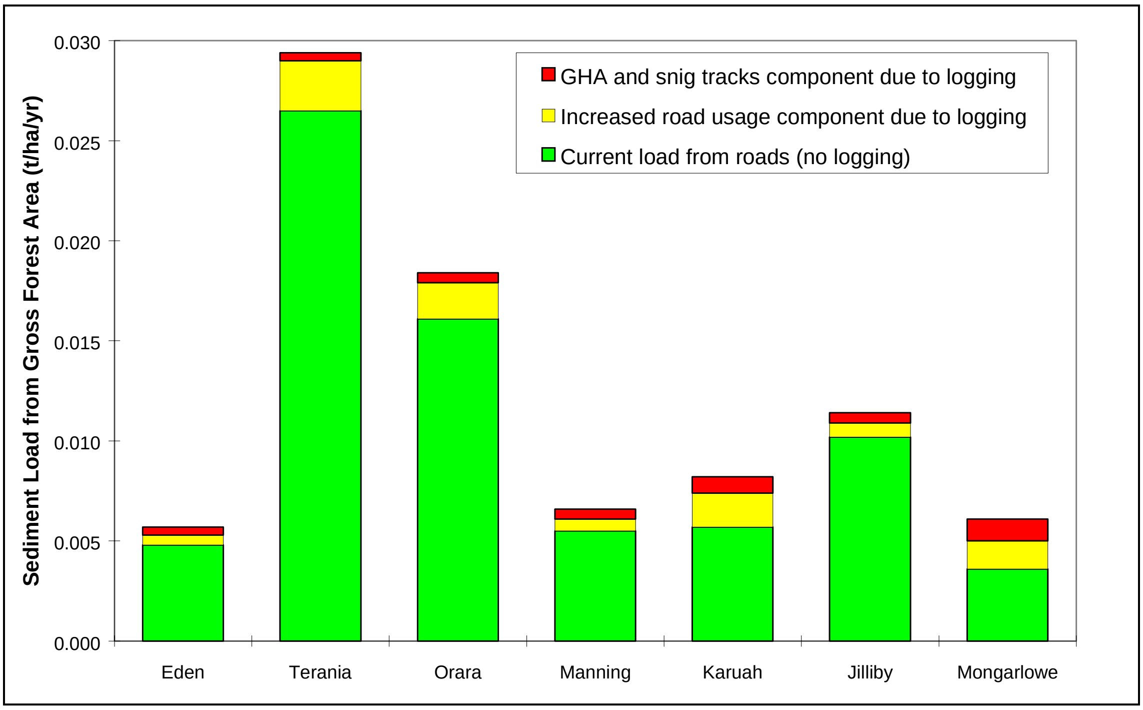

FIGURE 6.J SEDIMENT LOAD FOR LOGGING SCENARIOS

The estimated current loads from roads (no logging) and estimated load for the logging scenarios are summarised in Table 6.C. For the current conditions the highest sediment loads are calculated for the Terania and Orara catchments because they have the highest rainfalls. The increase in sediment load ranges from around 10 percent for Terania to around 70 percent for Mongarlowe and is a function of the logging scenarios and the rainfall.

TABLE 6.C ESTIMATED SEDIMENT LOADS

Catchment	Current load from roads (no logging) ($t/km^2/yr$)	Estimated load for logging scenario ($t/km^2/yr$)	Increase due to logging* (%)
Eden	0.5	0.6	20
Terania	2.7	3.0	10
Orara	1.6	1.8	10
Manning	0.6	0.7	20
Karuah	0.6	0.8	40
Jilliby	1.0	1.1	10
Mongarlowe	0.4	0.6	70

*Note: values rounded to nearest 10%

Typically sediment yields for catchments with an area of approximately 100 km^2 are approximately 10 to 1000 $t/km^2/yr$ (Milliman and Syvitski, 1992; Walling, 1983). Although Australian rivers are widely recognised as relatively low yielding on a world scale, the values listed in Table 6.C may be too low. However, even if the loads are underestimated, the method does provide a consistent basis for determining the *relative* impacts arising from logging activities.

6.6.1 Sediment Concentration

The average annual sediment load from the upstream forest area was calculated for the two downstream streamflow gauges and converted to an average concentration by dividing by the mean annual flow. It is possible that some of the sediment load will be stored within the channel and will not proceed further downstream and therefore a range of concentrations were calculated which reflect delivery efficiencies of between 50% to 100% of the generated load.

The estimated sediment concentrations are given in Table 6.D. The concentrations only represent the sediment load coming from the forests and thus the actual sediment loads measured at these locations will be higher than this because of the contribution from the agricultural areas.

TABLE 6.D ESTIMATED RANGE OF SEDIMENT CONCENTRATIONS

Catchment	Downstream of forest		Downstream of mixed land use	
	no logging (mg/L)	logging (mg/L)	no logging (mg/L)	logging (mg/L)
Eden	0.3 - 0.5	0.3 - 0.6	0.1 - 0.3	0.2 - 0.3
Terania	1.3 - 2.7	1.5 - 3.0	0.3 - 0.7	0.4 - 0.7
Orara	0.4 - 0.9	0.5 - 1.0	0.5 - 1.0	0.6 - 1.1
Manning	0.3 - 0.6	0.3 - 0.7	0.3 - 0.5	0.3 -0.5
Karuah	0.3 - 0.6	0.4 - 0.9	0.2 - 0.4	0.3 - 0.5
Jilliby	3.1 - 6.3	3.5 - 7.0	1.1 - 2.3	1.3 - 2.5
Mongarlowe	0.3 - 0.5	0.4 - 0.9	0.1 - 0.2	0.2 - 0.4

6.6.2 Downstream Context

Unfortunately there is a dearth of information on sediment loads which can be used to place the modelled values in a downstream context.

Turbidity is measured as part of the key sites program undertaken by the DLWC, however it is however not a direct measure of sediment load but rather a measure of the extent to which light passing through the water is scattered or absorbed (measured in Nephelometric Turbidity Units; NTU). The relationship between turbidity and suspended solids is site-specific and therefore without some information on suspended solids it is not possible to make estimates of sediment loads from turbidity data alone. Turbidity data is however useful for making qualitative assessment of the likely sediment concentrations.

Turbidity data is available downstream of four of the catchments, and this information is summarised in Table 6.E. The measurement sites are just downstream of the study catchments with the exception of the Manning catchment for which the measurement site is a large distance downstream and therefore the data may not be directly applicable to the study catchment. The guidelines for drinking water are for turbidity to be less than 5 NTU and therefore the turbidity for the 4 sites would be classified as “Good” (DLWC, 1998). Given the small relative increase in sediment loads estimated to occur due to logging, it would appear reasonable to assume that logging activities would not appreciably alter the turbidity rating.

TABLE 6.E TURBIDITY DATA (NTU) FROM KEY SITES PROGRAM

Catchment	Site	No. Obs.	Minimum	Median	Maximum
Eden	20310044 - Richmond River d/s Casino	43	1.2	5.0	95.0
Orara	204906 - Orara River @ Glenreagh	44	0.8	2.1	14.0
Manning	208004 - Manning River @ Killawarra	43	0.5	1.6	170.0
Karuah	209003 - Karuah River @ Booral.	22	0.7	4.4	27.0

7. CONCLUSIONS

The literature review undertaken for this study provides a thorough summary of our current understanding of the potential impacts of logging on catchment yield and water quantity. From the literature review of the impacts of logging on water yield, the following broad generalisations are well established:

- mean annual evapotranspiration (ET) is higher for forests than for grasslands;
- in south-eastern Australia, mean annual ET is higher in pine plantations than in native eucalypt forests, primarily due to differences in rainfall interception;
- afforestation of grasslands results in reductions in mean annual streamflow, low flows and high flows;
- forest clearance results in increases in mean annual streamflow, low flows and high flows; these increases are transient if the forest is permitted to regenerate;
- the degree of streamflow increases following forest logging is linearly proportional to the area of forest logged;
- in forests which are cleared but permitted to regenerate, streamflow increases usually peak in the first three years following treatment – streamflows normally return to pre-treatment levels between 4 and 10 years after disturbance, but may take as long as 25 years to recover;
- following the initial increase in yield, streamflow decreases to a minimum after about 30 years of age, followed by a gradual recovery back to old-growth conditions over the next 50 to 150 years (the exact timing and magnitude of the deficit and recovery are speculative);
- the streamflow impacts of forestry activities are amplified by increases in mean annual rainfall – absolute impacts are diminished in drier areas.

From the literature review of water quality, the following broad generalisations are well established:

Sediment and nutrient sources

- unsealed roads are the major sources of sediment in managed forests;
- road usage is a critical factor in explaining sediment production rates on roads;
- sediment yields from forested catchments are considerably lower than those from other land-uses, particularly agriculture;
- sediment production rates from roads and snig-tracks decline within the time-frame of 2 to 5 year after use is discontinued;

- nutrient concentrations in streams draining forested catchments are considerably lower than those reported for other land uses, primarily agriculture;
- the dominant cause of increased nutrients in streams if observed, is due to the effects of prescribed burning and wildfire;
- observed impacts of additional nutrient loads are short-lived and transient, with no long term effect.

Sediment delivery patterns

- channelised pathways forming at road drainage outlets form the most efficient conduit for sediment and nutrients;
- sediment delivery ratios are closely associated with the size composition of the in-situ and eroded soil.

Efficacy of Best Management Practices

- Best Management Practices play a significant role in the reduction of adverse effects in forested catchments;
- forested buffer strips are an effective measure in reducing the volume of surface water and sediment/nutrients delivered to a stream.

Use of predictive tools

- the use of simple empirical relationships for prediction is not scientifically defensible, though the lack of suitable input data and the difficulty of parameterisation hinders the applicability of physically-based procedures.

One of the principal objectives of this project was to develop a methodology for modelling the impact of logging on water quality and quantity. Models were developed specifically to suit the project objectives at a complexity commensurate with the available data. The models developed for the study are conceptually simple. While this lack of modelling complexity partly reflects the limited time available, the governing constraint is that there is not the data available to apply and validate more complex models at the required spatial and temporal scales. It is considered, however, that the adopted methodology provides a reasonable "best guess" that is unlikely to be much improved even with the expenditure of considerable further effort. Importantly, the developed methodology can be applied to all forests within the CRA regions.

The following conclusions can be made on the basis of the results obtained from the water yield modelling:

- the total expected *increase* in mean annual flow due to combined effects of both logging and tree growth ranges between 2% and 60%, and the corresponding total expected *decrease* is generally expected to be zero;
- the total expected *increase* in mean annual flow that is attributable solely to logging ranges between around 0% and 10%, and the corresponding total expected *decrease* in mean annual flow ranges between around 5% and 50%;
- the timing of these expected decreases and increases is dependent upon the current age of the forest and the adopted logging scenario; in general however, it is expected that the

streamflow increases solely attributable to logging will peak within the next 10 years, and the maximum decreases will occur within the next 40 to 80 years;

- the impacts attributable solely to logging are not sensitive to the initial age profile adopted;
- the total expected impact on yield due to both logging and growth will vary depending on the initial age profile adopted.

The following conclusions can be made on the basis of the results obtained from the water quality modelling:

- the total estimated increase in sediment loads due to logging activities range between 10% and 70% of the current estimated loads;
- the majority of the increase in sediment load is generated by increased road traffic;
- the contribution from the general harvest and snig track area represents between 10% to 40% of the total increase in sediment load due to logging.

The above results are subject to considerable uncertainty, though it must be stressed that the major output of this project is a modelling framework rather than a set of results that can be directly transposed to other regions. It is considered that the uncertainty of the model estimates does not detract from the ability of the models to provide information on the *relative ranking* of proposed measures. While the absolute magnitude of the estimates may be uncertain, the models do codify our current best understanding of the different factors that influence water quantity and quality within the limitations of current data availability. The models thus provide a robust, credible, and objective basis for evaluating the impacts of logging, particularly if used to rank proposed activities in terms of relative disadvantages and merits.

8. RECOMMENDATIONS

The results arising from this study should be regarded as "best estimates" that are suitable for preliminary planning purposes. There are a number of limitations that are the result of time constraints imposed on the project. Some of these issues could be readily resolved within perhaps a two month time frame, and hence it is recommended that:

1. Further efforts be made to refine a set of site-specific and generic logging scenarios.
2. The method used to derive current forest age should be reviewed to determine whether or not the estimates of the current age profile can be improved upon.
3. Sensitivity analyses should be undertaken to determine how the salient assumptions adopted impact upon the results.
4. Detailed information should be obtained on the drainage network of a forested area and used to assess the validity (and/or to adjust) the stream density relationships derived in this study.
5. The likely benefits of discriminating between different road classes for the determination of separate sediment delivery ratios should be assessed, and then implemented if found to be significant.
6. More data on representative rainfall characteristics should be derived for the catchments of interest.
7. Characteristics on forest age profile and sediment delivery ratios should be derived separately for the harvestable and reserved areas of the forest.
8. A review of project outcomes should be undertaken that involves the:
    - holding of a workshop to disseminate details of the methodology and results
    - provision of comments by stakeholders and external experts
    - preparation of a paper that summarises salient issues and concerns
9. Impacts should be derived for all major forests in the regions once the modelling methodology has been refined.

In addition to the above recommendations, there were a number of issues during the course of the study that could not be considered because of the constraints imposed on the project. The following issues may warrant further investigation:

- the effect of the NSW Water Reforms, in particular the NSW Government Interim Environmental Objectives for Water Quality and River Flow Objectives and the NSW Vegetation Reforms.
- The effect of logging on water quality characteristics other than suspended sediment, eg nutrients, changes in dissolved oxygen and pH (however there are very little data on these issues for Australian systems).

- The effects of forests on riverine habitat which includes the effects on riparian vegetation, streambank stability and fauna and flora populations.
- The cumulative effects of past forest practices on both water quantity and quality.
- The impact of logging on yields at a monthly or seasonal temporal scale. (Insufficient information exists for seasonality to be incorporated within the adopted modelling approach however seasonal impacts of loggings could be investigated in a speculative manner by the application of more physically based modelling at a finer resolution timestep).

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APPENDIX A -
LIST OF CONTACTS

Name	**Organisation**	**Nature of Contact**
Hoare, James	Bureau of Resource Sciences	Stakeholder input
O'Shaughnessy, Pat	Consultant	General approach
Croke, Jacky	CSIRO Division of Land and Water	Provision of expert advice on sediment yield modelling
Hairsine, Dr. Peter	CSIRO Division of Land and Water	Provision of expert advice on sediment yield modelling
Vertessy, Dr. Rob	CSIRO Division of Land and Water	Provision of expert advice on water yield modelling
Briones, Julito	Department of Land and Water Conservation	Provision of GIS information (stressed rivers, stream network)
Cross, Hugh	Department of Land and Water Conservation	Availability of water quality data
Dwyer, Mick	Department of Land and Water Conservation	Provision of GIS information and Regional Data Manager Contacts
Daly, Helen	Department of Land and Water Conservation	Provision of water quality data
Harris, Justine	Department of Land and Water Conservation	Provision of information on stressed rivers and water quality data
Reid, Bruce	Department of Land and Water Conservation, Hunter Region	Availability of detailed GIS stream network
Taylor, Scott	Department of Land and Water Conservation, North Coast Region	Provision of water quality data
Whitty, Ray	Department of Land and Water Conservation, North Coast Region	Availability of detailed GIS stream network
Davis, Michael	Department of Urban Affairs and Planning	Client contact
Hartley, Stephen	Department of Urban Affairs and Planning	Stakeholder input
Lead, Stephen	Department of Urban Affairs and Planning	Supplied information on GIS data availability used in CRA process
Ross, John	Department of Urban Affairs and Planning	Supplied information on GIS data availability used in CRA process
Thomson, Sarah	Environment Protection Authority	Stakeholder input
Clidesdale, Peter	LIC (Surveyor General's Office)	Availability of detailed stream network

Name	Organisation	Nature of Contact
Brieley, Gary	Macquarie University	Water quality data and availability of detailed stream network
Muirhead, Ian	National Climate Centre	Meteorologic data for study areas
Greg Hall	Nature Conservation Council	Stakeholder input and assessment of forest age profile
Orrego, Lyn	North East Forest Alliance	Stakeholder input
Felicity Faulkner	National Parks Wildlife Service	GIS information on national park boundaries
Mezzatesta, Robert	National Parks Wildlife Service	GIS information on national park boundaries
Packard, Paul	National Parks Wildlife Service	Stakeholder input
Nolan, Pauline	South East Forest Alliance	Stakeholder input
McKee, Lester	Southern Cross University	Water quality data
Brand, David	State Forests	Stakeholder input
Bridges, Bob	State Forests	Information on plausible logging scenarios
Carter, Phillip	State Forests	Availability of information on age profile of forests.
Cornish, Peter	State Forests	Provision of expert advice on water and sediment yield modelling
Cowgill, Russell	State Forests	Stakeholder input
Emily Gao	State Forests	Provision of GIS information (CRA regions, forest structure, modelled stream network, roads, compartment boundaries)
Lacey, Steve	State Forests	Provision of GIS information regarding stream layers
Loane, David	State Forests	Provision of GIS information (CRA regions, forest structure, modelled stream network, roads, compartment boundaries)
Maher, Ron	State Forests	Provision of GIS information (CRA regions, forest structure, modelled stream network, roads, compartment boundaries)
Moore, Tom	State Forests	Provision of GIS information regarding stream layers
Moxon, Ken	State Forests	Data base of forest history
Parry, Jacky	State Forests (Northern Rivers Region)	Information on plausible logging scenarios
Rayson, Steve	State Forests (Mid North Coast Region)	Information on plausible logging scenarios
Sharpe, Paul	State Forests (Manning Region)	Information on plausible logging scenarios
Simmons, Jim	State Forests (Hunter Region)	Information on plausible logging scenarios
Williams, Bob	State Forests (Northern Rivers Region)	Information on plausible logging scenarios

APPENDIX B - LIST OF INCOMING DATA

Incoming data and sources (excluding additional literature review material):

Document reference		Source
1.	Aquatic environment survey report - Casino and Murwillumbah Management areas, Northern Region, State Forests of NSW by David Balloch (1993)	Peter Cornish
2.	Beavis, S, & Oke, A. (1998) Hydrology of the Upper North East CRA Region, internal report as a part of the NSW CRA/RFA process	DUAP (Michael Davis)
3.	Central Highlands, CRA report (chapt 9 only), NRS. Relevant to Victoria only, includes refs. to water yield impacts.	Michael Davis
4.	Comprehensive Regional Assessment, W.A. Includes ref on water quality/quantity.	Michael Davis
5.	Cornish, Dr P M; State Forests of NSW, Sydney; Water Yields in the Wallagaraugh River Catchment: a Preliminary Assessment of Forestry Impacts; July 1997.	Pat O'Shaughnessy
6.	Cornish, P M; The Effects of Radiata Pine Plantation Establishment and Management on Water Yields and Water Quality - A Review; Technical Paper No. 49; Hydrology Section, Wood Technology and Forest Research Division; Forestry Commission of New South Wales; Sydney; 1989.	Pat O'Shaughnessy
7.	Cornish, P.M. (1996). Modelling water yield in forests.	Peter Cornish
8.	Cornish, P.M. and Vertessy, R.A. (1998). Evaporation and forest age: observations in a regenerating eucalypt forest in Eastern Australia.	Peter Cornish
9.	CRCCH Industry Report, (1997) Controlling Sediment and Nutrient Movements within Catchments	Personal Copies
10.	CRCCH Industry Report, (1998) Predicting Water Yield from Mountain Ash Forest Catchments	Personal Copies
11.	Croke, J and Fogarty, P; Erosion in Forests, Proceedings of the	Pat O'Shaughnessy

	Forest Erosion Workshop, March 1997; Report 98/2; Cooperative Research Centre for Catchment Hydrology; March 1998.	
12.	CSIRO Forestry and Forestry Products and Andrew Smith, Setscan and Pat O'Shaughnessy & Associates; Assessment of Forest Management Practices for the Eden RFA; New South Wales Government, June 1997; Commonwealth Government June 1997 Forests Taskforce Department of Prime Minister and Cabinet.	Pat O'Shaughnessy
13.	CSIRO Land and Water; Quantifying the Redistribution of Soils and Sediments Within a Post-harvested Forest Coupe Near Bombala, New South Wales, Australia; CSIRO Land and Water Technical report no. 7/97, August 1997.	Pat O'Shaughnessy
14.	Dargavel, John; Hamilton, Clive; O'Shaughnessy, Pat; The Australia Institute; Logging and Water; Discussion Paper Number 5; November 1995.	Pat O'Shaughnessy
15.	Davies, P.E., & Nelson, M. (1993) The effect of steep slope logging on fine sediment infiltration into beds of ephemeral and perennial streams of the Dazzler Range, Tasmania, Australia, Journal of Hydrology, 150, 481-504	Copy from Library
16.	Department of Land & Water Conservation; Monitoring and Review Program: A Proposal for Evaluating the Inherent Soil Erosion and Water Pollution Hazard Assessment Model; Environment Protection Authority; State Forests of NSW; April, 1998.	Pat O'Shaughnessy
17.	DLWC (1998) Stressed Rivers Project: Hydrologic Analysis	Justine Harris, DLWC
18.	DLWC (1998), Monitoring and Review Program: A Proposal for Evaluating the Inherent Soil Erosion and Water Pollution Hazard Assessment Model	Peter Cornish
19.	EIS Management Team, State Forests of NSW (1996) Modelling Long-term Catchment Turbidity Changes in Forests	Cornish (fax)
20.	Environmental Flow rules for the following catchments: Hunter, Gwydir, Barwon-Darling, Lachlan, Macquarie, Murrumbidgee, Namoi : These are all brief pamphlets that provide an overview of the water resources in the valleys, and provide quantitative flow rules for the catchments.	Michael Davis
21.	EPA, Proposed Interim Environmental Objectives for NSW Waters; Coastal Rivers, 1997	Sarah Thomson, EPA
22.	EPA, State Forests, DLWC, (1997) Soil Erosion and Water Pollution Hazard Assessment for Logging Operations	Jackie Croke
23.	ESFM Performance Indicators - Soil and Water	Jackie Croke
24.	Far South Coast Catchment Management Committee, NSW; Bemboka Catchment; Final Report on Interactions Between Land Use and Water Resource Availability and Security; Gutteridge Haskins & Davey Pty Ltd; April 1997.	Pat O'Shaughnessy
25.	Gloucester and Chichester Forestry management Areas, EIS, Hydrology and Water Quality. CMPS&F. Useful example of impact assessment due to forest management practices, both water	Michael Davis

	quantity and water quality.	
26.	Grayson, R.B. *et al.* (1993) Water quality in mountain ash forests - separating the impacts of roads from those of logging operations, Journal of Hydrology, 150, 459-480	Copy from Library
27.	Harper, P B and Lacey, S T; A Review of Findings From The Yambula Catchments Forest Hydrology Research Project 1997-1990; Research Paper No. 33; Forest Research and Development Division, State Forests of New South Wales, Sydney, 1997.	Pat O'Shaughnessy
28.	Hassal & Associates Pty Ltd, Economic Impacts of Interim River Flow Objectives: Uncontrolled Coastal Streams, 1996	Sarah Thomson, EPA
29.	Hydrology of the Eden CRA Region. Useful report relevant to dry southern forests, and includes refs to water quality/quantity impacts.	Michael Davis
30.	Lacey, S.T., Soil Erosion and Runoff Measurement on Steep Forest Sites in Northern NSW	Copy, Croke *et al.*
31.	Maidment, David R; Davis, George H; McGulloch, J S G; Nash, J E; European Geophysical Society; Journal of Hydrology; Vol. 150 - No's 2-4; Elsevier Science Publishers; 1993.	Pat O'Shaughnessy
32.	Melbourne Water, (1994) Water Yield Investigations from the Betka River Catchment for Mallacoota Water Board	Brad Neal (SKM)
33.	Modelling water yield in the catchment of Rocky Creek Dam by P.M. Cornish (1997)	Peter Cornish
34.	Notes on Yambulla forest study and preliminary results	Peter Cornish
35.	NSW Draft ESFM Technical Framework	Pat O'Shaughnessy
36.	NSW ESFM Background Report	Pat O'Shaughnessy
37.	NSW Water Reforms DWLC (1997). Useful context to which we should refer to in final report.	Michael Davis
38.	NSW Weirs Policy, DLWC (1997). Not particularly useful.	Michael Davis
39.	O'Shaughnessy, P., Fogarty, P., & Croke, J. Practical Outcomes of the Workshop	Copy from Jackie Croke
40.	Pat O'Shaughnessy, Eden EIS, (folder)	Pat O'Shaughnessy
41.	Pollution Control Licence; Issued under Section 17A(b) Pollution Control Act, 1970; Licence Number: 4017.	Pat O'Shaughnessy
42.	Red Hill Hydrology, Very Preliminary Results	Pat O'Shaughnessy
43.	Regional Report of the upper North East New South Wales: Water Attributes (vol 3) and Physical Attributes (vol 2). Contains useful public lands map of forest and d/s areas. Quite detailed summary of hydrology and water resources in the region, as well as climate, soils, and geomorphology.	Michael Davis
44.	Renard , K.G. & Friemund, J.G. (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE, Journal of Hydrology 157, 287-306	Copy from Library
45.	Roberts, S.L., Vertessy, R.A. & Grayson, R. (1998) Transpiration	Rob Vertessy

	in Eucalyptus Sieberi Forests of Different Age, CRCCH	(CRCCH)
46.	Ryan, Dr Philip J; A Review of Land Evaluation and Other Procedures to Assess Soil Erosion and Water Pollution Hazard for Logging Operations; CSIRO Division of Forestry and Forest Products; Canberra; November 1996.	Pat O'Shaughnessy
47.	Sadek, T.M., Grayson, R.B., & Gippel, C.J., The Impact of Roads and Landslides on Stream Water Turbidity and Suspended Sediment in Forested Catchments, CRCCH	Copy, Croke *et al.*
48.	Schedule 3: Methods for assessing the soil erosion and water pollution hazard associated with logging operations	Copy
49.	Schofield, N.J. (1996) Forest management impacts on water values, Recent Research Developments in Hydrology	Rob Vertessy (CRCCH)
50.	Securing our Water Future, Stressed Rivers Assessment Report: NSW State Summary, DLWC	Justine Harris, DLWC
51.	Securing our water future. NSW Water reforms (1997). Perhaps adds little to items 11 and 12.	Michael Davis
52.	Some effects of logging on water quality and water yield in the Karuah hydrology research catchments, by P.M. Cornish (1991) - paper presented to the IFA meeting on old growth forest, Dungog, NSW	Peter Cornish
53.	Stream turbidities in the Karuah and Bellinger Valleys by Peter Cornish	Peter Cornish
54.	Stressed Rivers Assessment Discussion Paper and Method Report (draft)	Justine Harris, DLWC
55.	Tenterfield Management Area - Report to the Minister for Urban Affairs and Planning on EIS Representations, Draft Appendences, State Forests of NSW (1996)	Peter Cornish
56.	Turner, John; Lambert, Marcia; Dawson, John; Water Quality Monitoring Strategies for Forest Management: a Case Study in the Towamba Valley Catchment; Research Paper No. 31; Forest Research and Development Division, State Forests of New South Wales, Sydney, 1996.	Pat O'Shaughnessy
57.	Turner, John; Lauck, Veronica; Dawson, John; Lambert, Marcia; Water Quality Monitoring Strategies for Forest Management: a Case Study at Bago State Forest; Research Paper No. 30; Research Division, State Forests of New South Wales, Sydney, 1996.	Pat O'Shaughnessy
58.	Update, Newsletter of NSW Water reforms. March and June 1998. Useful overview of stressed rivers and environmental health programs.	Michael Davis
59.	Water Resources and Management, BRS, SE Qld CRA (1998). Does not at first glance look that useful, may have information of relevance to dry northern forests?	Michael Davis
60.	Water Resources of the Namoi Valley (1970: Detailed review of water resources, no water quality info.	Michael Davis
61.	Water sharing in NSW - access and use, DLWC (1998). Useful	Michael Davis

	context to which we should refer to in final report.	
62.	Watson, F. et al (1998) Effect of Forestry on the Hydrology of Small Experimental Catchments CRCCH Draft Report	Rob Vertessy (CRCCH)
63.	Wilson, C. Simple Relationships between disturbance, rainfall intensity, runoff and erosion in a Tasmanian Forest	Copy, Croke *et al.*
64.	Wilson, Dr. C. & Lynch, T. The Impact of Logging on Turbidity Values in Muselboro Creek, Tasmania	Copy

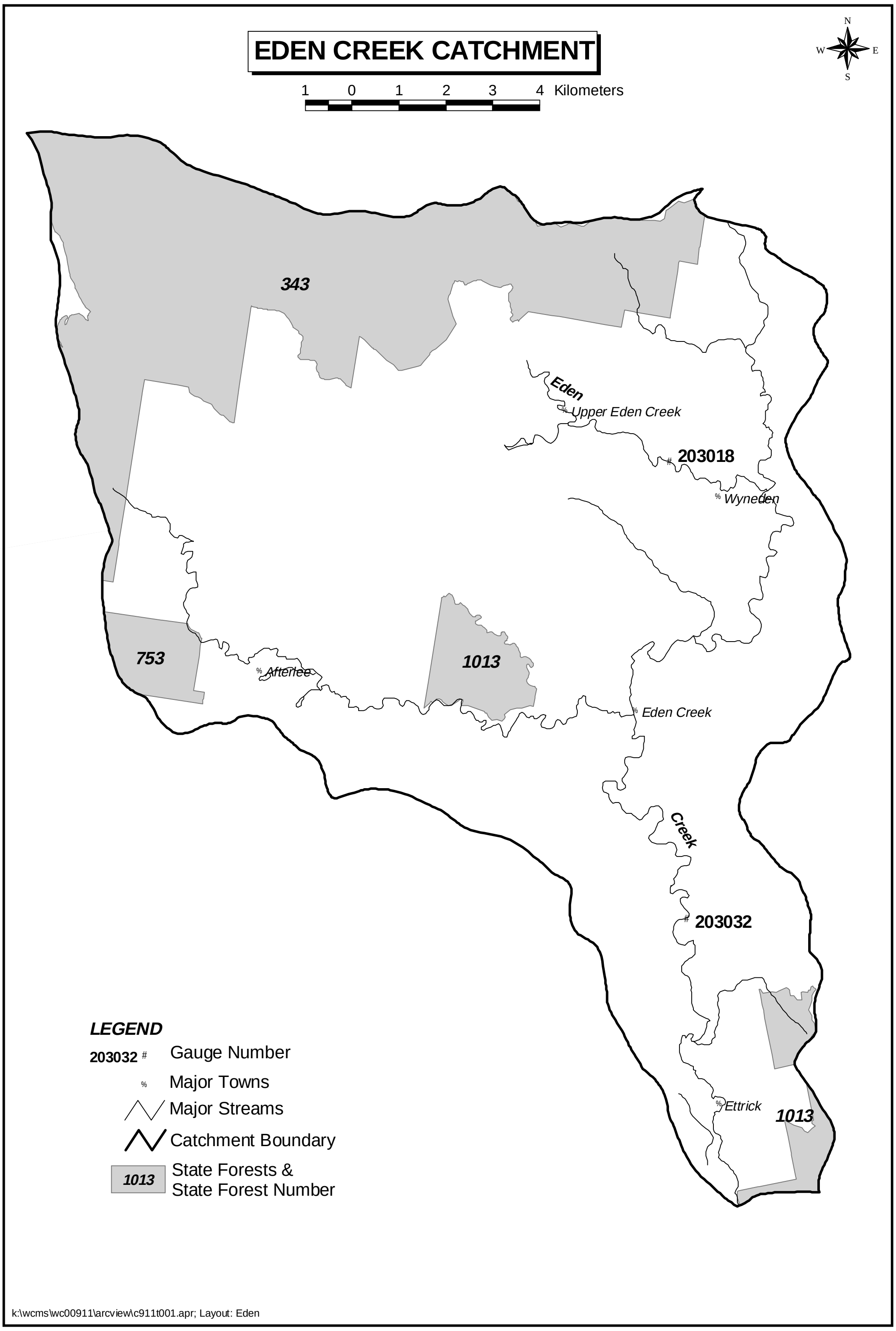
Incoming GIS Data:

Received	From	Media	Description
24/8/98	Julito Briones (DLWC)	email	stressed rivers subcatchments
26/8/98	Julito Briones (DLWC)	FTP	major rivers and stressed rivers subcatchments
27/8/98	Julito Briones (DLWC)	FTP	location of streamflow gauges
28/8/98	Felicity Faulkner (NPWS)	CD-ROM	boundary of areas under management of NPWS including National Parks, Nature Reserves, Regional Parks, Sate Recreation Areas, Aboriginal Areas and Historic Sites
28/8/98	Emily Gao (SFNSW)	CD-ROM	forest type, vegetation structures, inherent hazard classification, regolith, methodology documentation file, flow charts, CRA boundaries for UNE and LNE
2/9/98	John Ross (DUAP)	FTP	GIS layers showing subcompartments, downloaded from ftp.erin.gov.au/forest/nwsupper/tenure/planunt.zip
3/9/98	Emily Gao (SFNSW)	email	compartment boundaries for Southern Region in Zone 55, compartment boundaries for Southern Region in Zone 56, compartment boundaries for LNE, CRA southern boundary, Roads for LNE, Roads for Southern Region in Zone 55,
9/9/98	Julito Briones (DLWC)	email	DLWC stream layer
10/9/98	Emily Gao (SFNSW)	CD-ROM	1:25,000 LIC stream network for UNE 1:25,000 LIC stream network for LNE 1:25,000 LIC stream network for Southern (Zone 55) 1:25,000 LIC stream network for Southern (Zone 56) roads for UNE
10/9/98	Emily Gao (SFNSW)	CD-ROM	Stream network and buffers modelled by Tom Moore Forest types for UNE and LNE
11/9/98	Russell Cowgill (SFNSW)	CD-ROM	management history for UNE & LNE
11/9/98	Emily Gao (SFNSW)	email	Operational roads for SF947, Operational roads for Southern Region in Zone 56, Forest types for SF947

Incoming Miscellaneous Electronic Data:

Received	From	Media	Description
21/8/98	Sarah Thompson	email	data on Northern Rivers Water Quality
25/8/98	Justine Harris (DLWC)	email	appendices from stressed rivers report
26/8/98	Rob Vertessy (CSIRO)	disk	flow data for Karauh catchment
27/8/98	Justine Harris (DLWC)	email	draft report outlining hydrology for stressed rivers
27/8/98	Stephen Lead (DUAP)	email	EPCRA1.xls - spreadsheet containing information on eucalyptus plantations (age etc.)
8/9/98	Justine Harris (DLWC)	email	Spreadsheet of water usage for stressed river subcatchments
8/9/98	Ian Muirhead (BoM)	FTP	pluviograph data for 069062, 058099, 061158
10/9/98	Justine Harris (DLWC)	email	Spreadsheet of suspended solids data for stressed river subcatchments
11/9/98	Emily Gao (SFNSW)	email	state forest road classifications

APPENIDIX C - CATCHMENT MAPS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LEGEND
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Major Streams
Catchment Boundary
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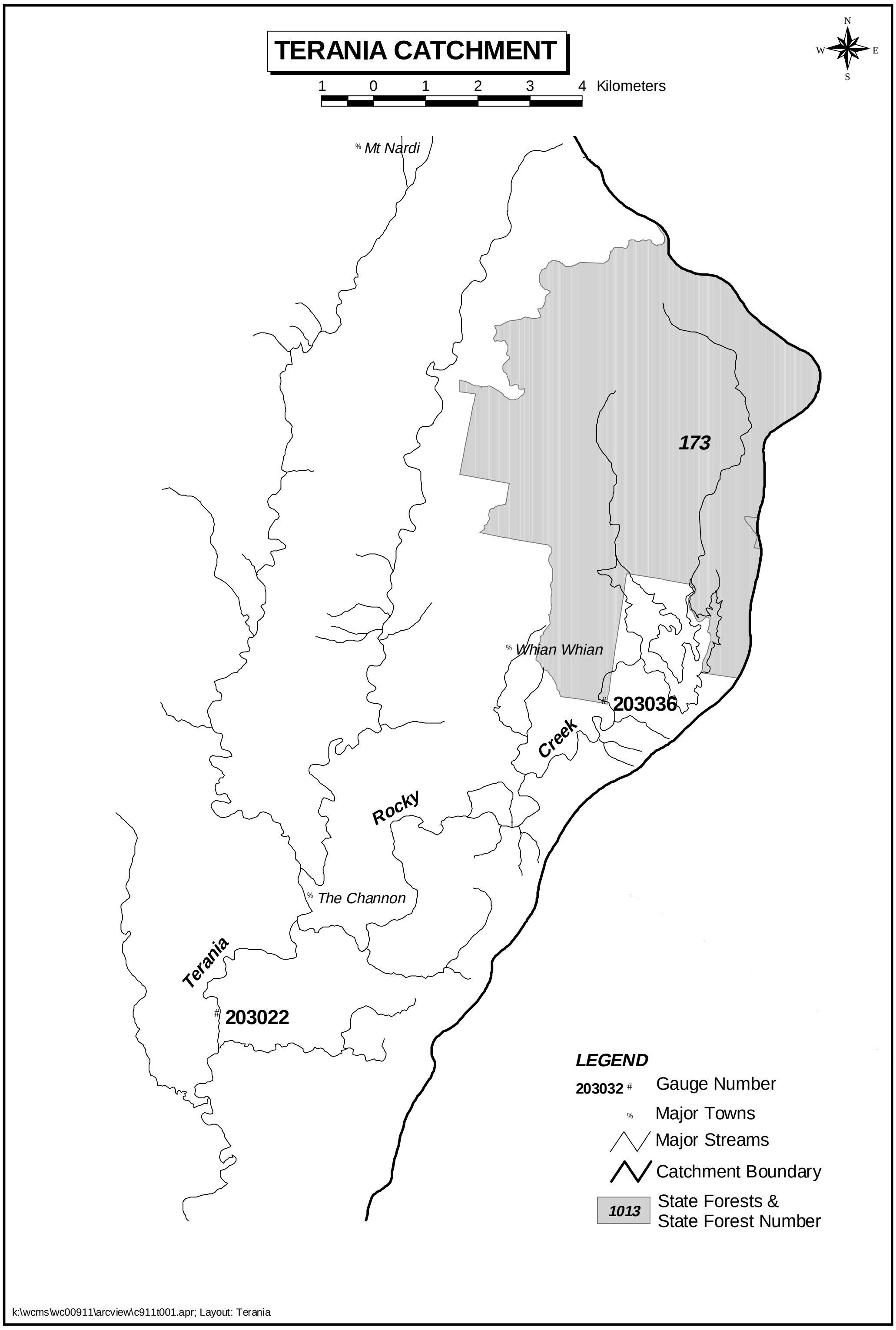
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LEGEND
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Major Towns
Major Streams
Catchment Boundary
1013 State Forests & State Forest Number
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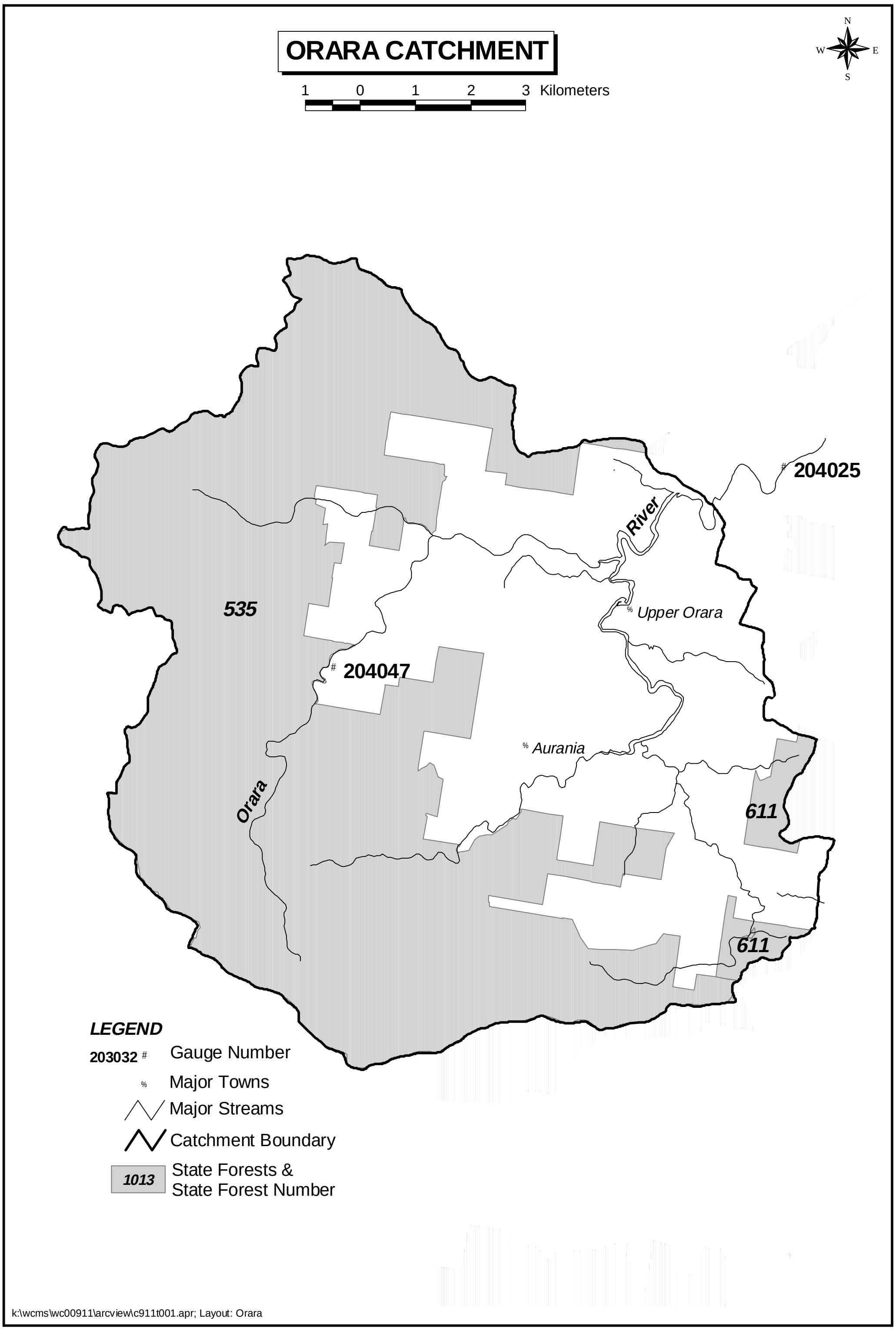
ORARA CATCHMENT
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Major Streams
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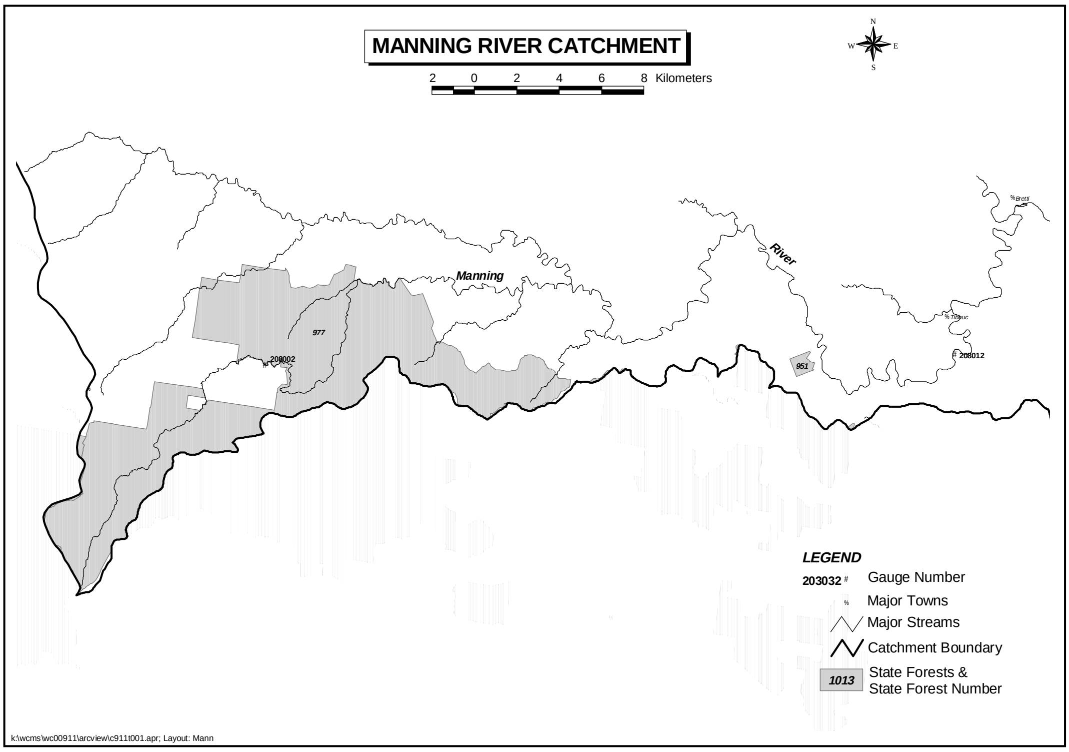
MANNING RIVER CATCHMENT
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Major Towns
Major Streams
Catchment Boundary
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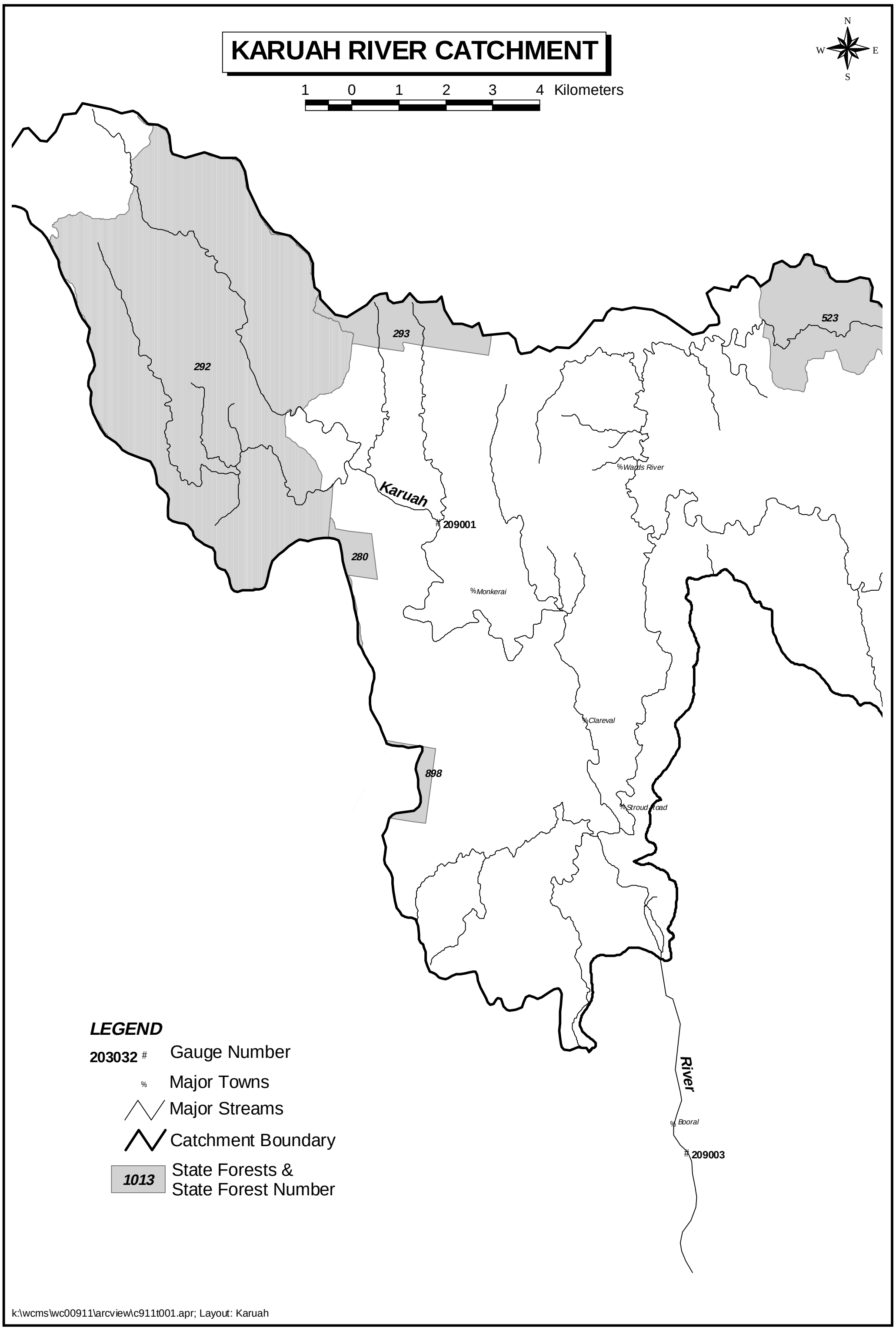
KARUAH RIVER CATCHMENT
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292
293
523
280
898
Karuah
River
209001
209003
Monkerai
Wards River
Clareval
Stroud Road
Booral
LEGEND
203032 Gauge Number
Major Towns
Major Streams
Catchment Boundary
1013 State Forests & State Forest Number
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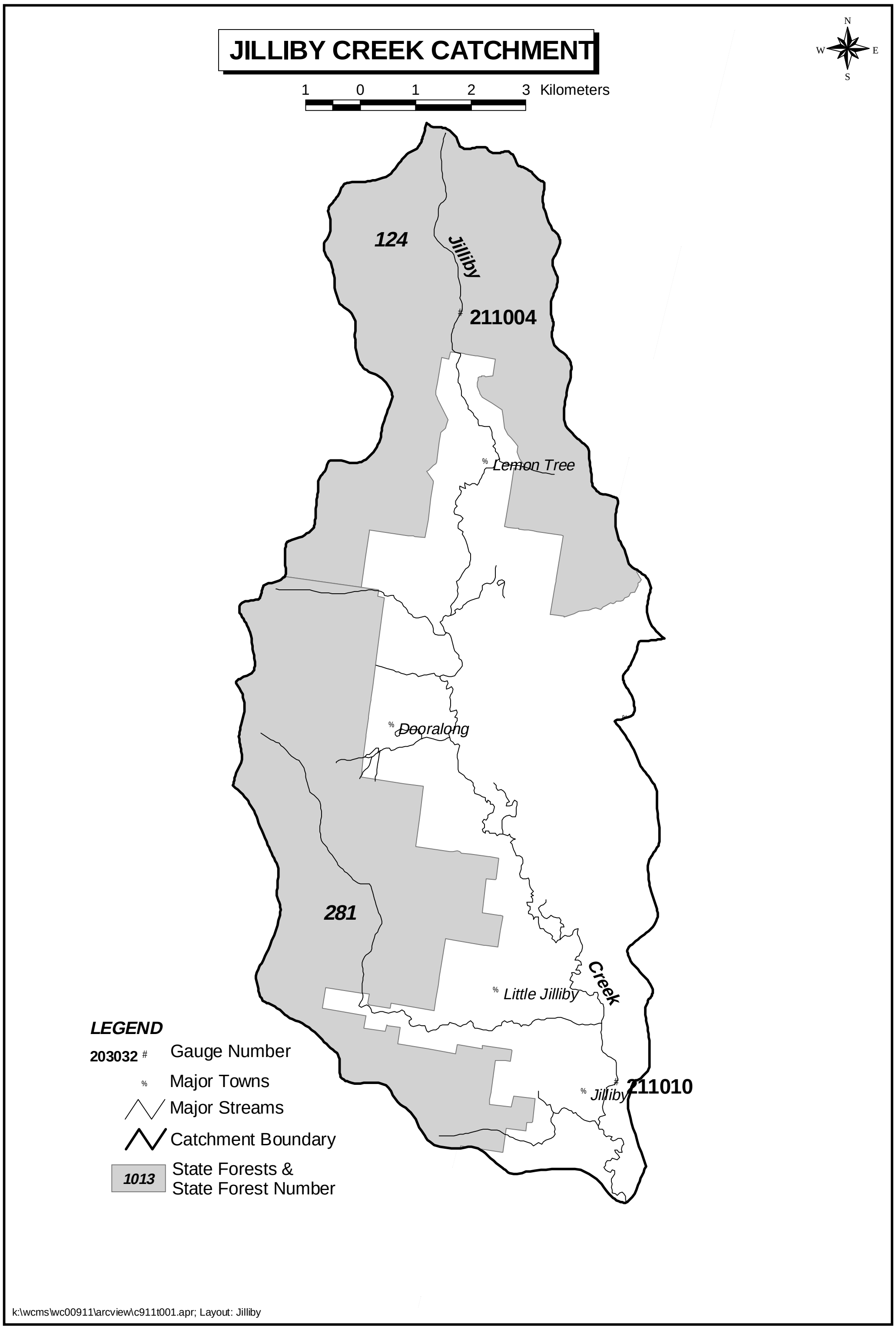
JILLIBY CREEK CATCHMENT
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211004
Lemon Tree
Dooralong
281
Little Jilliby
Creek
Jilliby
211010
LEGEND
203032 # Gauge Number
Major Towns
Major Streams
Catchment Boundary
1013 State Forests & State Forest Number
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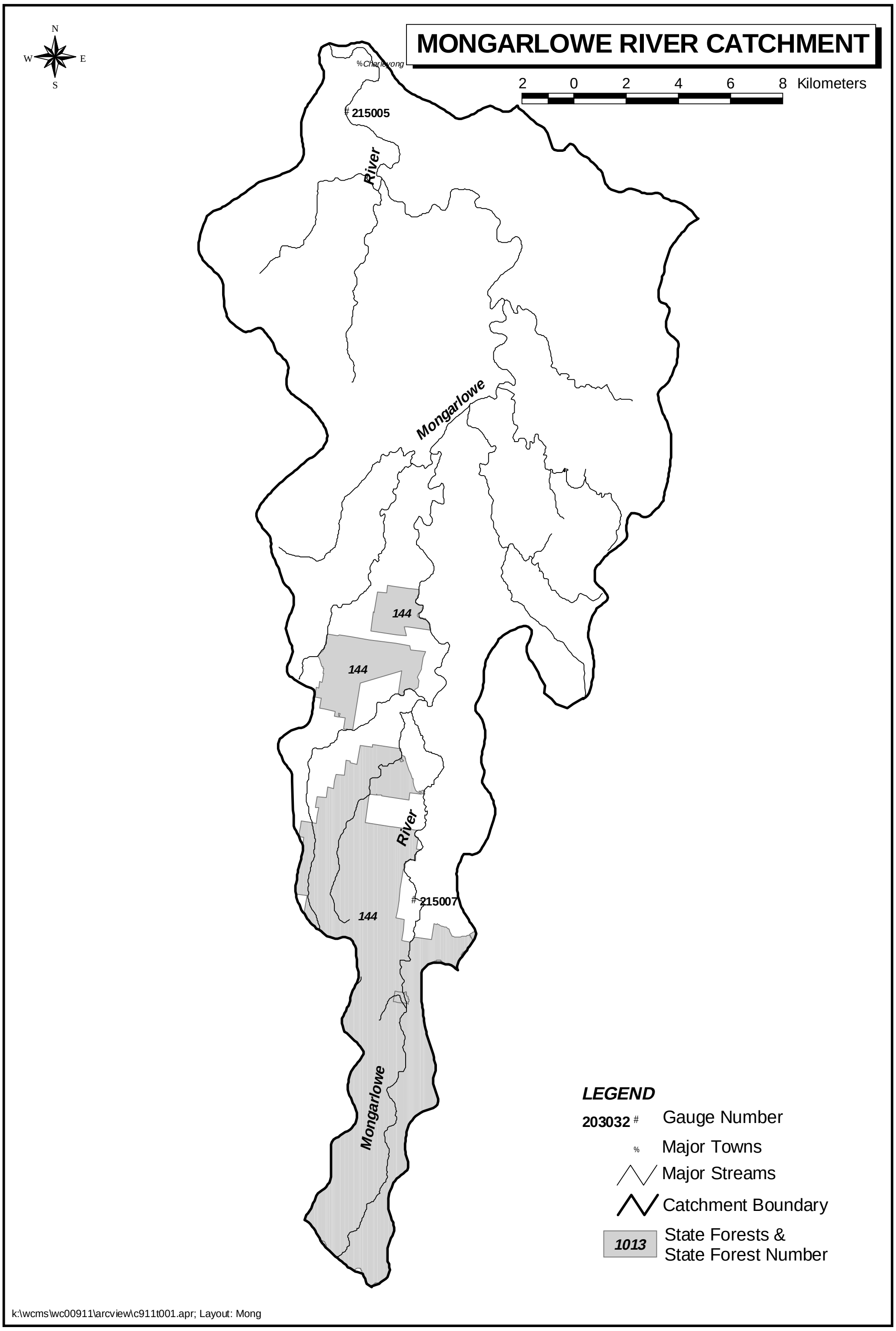
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203032 # Gauge Number
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Major Streams
Catchment Boundary
1013 State Forests & State Forest Number
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APPENDIX D - STRESS SIGNIFICANCE MAPS