FOREST DENSITY REDUCTION IN A SMALL CATCHMENT OF THE NORTHERN JARRAH FOREST AND THE EFFECT ON WATER AND WOOD PRODUCTION

Forest Density Reduction in a Small Catchment of the Northern Jarrah Forest and the Effect on Water and Wood Production

by

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This thesis is submitted for the degree of

Master of Science

in the Botany Department of the University of
Western Australia.

February 1990

Declaration

Except where otherwise indicated this thesis is my own work.

Acknowledgements

I take this opportunity in thanking the following:

* Chris Portlock, Brett Glossop, Peter Summerford, Darryl Glover, Tim Foley and Brad Barton for their technical assistance without which this thesis would not have been possible.
* David Bell my supervisor.
* My predecessors Syd Shea, Eugene Herbert and Peter Ritson who originated much of the hydrologic work.
* Syd Shea who encouraged me to start this thesis.
* Guilia Maranta for typing the manuscript and drafting the figures.
* Alcoa of Australia for financial assistance to treat the Yarragil 4L catchment.
* The Forests Department and more lately the Department of Conservation and Land Management. In particular, the present and past staff of the Dwellingup Research Centre.

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Glossary

groundwater - All saturated water which is stored in the soil mantle.

growth efficiency - The annual growth of bole wood per unit of leaf area.

interception - All water evaporated or subliminated from rain or snow caught by living or dead plant material.

rainfall zones - as an aid to management in the jarrah forest these have been divided into:

high rainfall zone - > 1100 mm yr^{-1}

intermediate rainfall zone - > 900 to 1100 mm yr^{-1}

low rainfall zone - < 900 mm yr^{-1}

saltfall - Quantity of salt in rainfall.

saltflow - Quantity of salt in streamflow.

soil water - All unsaturated water which is stored in the soil mantle.

stages of development of jarrah:

ground coppice - Where the longest shoot is less than 1.5 m in length, the lignotuber is obvious and the length of the longest axis of the lignotuber is less 15 cm.

stump coppice - Resprouts from stumps cut above ground level, normally during logging.

sapling - Shoot more than 1.5 m in height but less than 15 cm diameter at breast height over bark.

pole - With a diameter at breast height over bark between 15 cm and 45 cm.

pile - With a diameter at breast height over bark between 45 cm and 60 cm.

tree - With a diameter at breast height over bark greater than 60 cm. Also used more generally to refer to plants capable of growing to this size.

stand growth - The sum of the growth of all stems on a unit area, usually expressed as m^2 ha^{-1} yr^{-1} of basal area or m^3 ha^{-1} yr^{-1} of volume.

stemflow - That portion of rainfall which is caught by the vegetative canopy and then flows down the plant stems to the ground.

stocking - The number of stems per hectare.

streamflow - All water that flows out of a catchment in the stream channel.

throughfall - That portion of rainfall that reaches the forest litter through spaces in the vegetative canopy and as drip from leaves, twigs and stems.

transpiration - All water in plants which is transferred to the atmosphere through the stomata of living leaves of plants.

tree growth - The growth of an individual, or the average growth of a number of individual stems, usually expressed as cm yr^{-1} of diameter.

water use efficiency - The ratio of plant growth to plant water use.

Summary

Water and wood production are two of the most important products from the northern jarrah forest of Western Australia. Both of these products have short supply, but are subject to increasing demand. The objective of this study was to test the hypothesis that the thinning of an uneven-aged jarrah forest catchment will increase both water and wood production.

A first order catchment of 125 ha was selected to be thinned and streamflow was measured from 1976 for this catchment and a group of control catchments. Similarly, groundwater levels were measured at a valley and a midslope location in the catchment to be thinned and a group of control catchments. Regression equations were established from the pretreatment data and used to predict changes in streamflow and groundwater level following thinning. The diameter, height and utilization status of jarrah trees in various size classes and site-types in the thinned catchment and surrounding unthinned control stands were measured in 1985. Diameters were remeasured in 1986 and growth in diameter, basal area and volume calculated.

The catchment was thinned early in 1983 reducing stocking, basal area and leaf area index by about two-thirds. The catchment has an average annual rainfall of 1120 mm and had an average annual streamflow prior to thinning of 4.3 mm. Rainfall during the study period was 15 per cent below the long term average and this would have affected the magnitude of the responses to thinning but not the general trends. The forest was uneven-aged and composed of the full range of tree sizes and ages. The younger and more vigorous trees were retained in the thinning because (i) the younger and more vigorous trees within each size class were selected for retention and (ii) a slightly higher proportion of smaller and thus younger trees in the thinned stand relative to the unthinned stand.

Thinning increased tree and stand growth of jarrah in all size classes and most site-types. Average diameter growth for the unthinned jarrah trees was 0.16 cm yr^{-1} compared with 0.64 cm yr^{-1} for the thinned trees. Average basal area growth of jarrah for the unthinned stands was 0.12 m^2 ha^{-1} yr^{-1} compared with 0.30 m^2 ha^{-1} yr^{-1} for the thinned stands. Average volume growth of jarrah for the unthinned stands was 0.98 m^3 ha^{-1} yr^{-1} compared with

1.90 m^3 ha^{-1} yr^{-1} for the thinned stands. Merchantable volume growth increased. For the veneer and general purpose sawlog components, volume growth of jarrah increased from 0.14 m^3 ha^{-1} yr^{-1} for the unthinned stands, to 0.48 m^3 ha^{-1} yr^{-1} for the thinned stands. Thinning concentrated growth onto trees with a better utilisation status.

In the first year following the thinning there was not a significant increase in streamflow in comparison with that predicted from regressions with control catchments. In the second year there was a small increase of 3.0 mm ± 1.1 mm which is equal to an increase of 58 per cent over the predicted streamflow. The third year showed an increase of 31.9 mm ± 2.0 mm which is equal to an increase of 541 per cent over the predicted streamflow.

The groundwater level in the midslope borehole rose at the rate of one m yr^{-1} in comparison with control boreholes and after four years the groundwater level had risen four metres. For the valley borehole the groundwater level showed little increase in the first year and a two m rise in the second year after thinning. In the third and fourth years groundwater level in the valley borehole did not rise further in comparison with control boreholes.

The increase in stand growth of jarrah despite the two-thirds reduction in leaf area index is because of an increase in growth efficiency, which in turn is due to the reduction in competition. For these uneven-aged stands the increase in growth efficiency was so great that an increase in stand growth resulted. This is because the relatively young and vigorous retained trees responded particularly well to the reduction in competition.

It is argued that the transpiration and interception components of the catchment water balance have reduced. However, these reductions have been matched to a large extent by increases in soil water and groundwater. Thus, the result is the observed relatively small and delayed response in streamflow. The rise in groundwater level following thinning has the potential to cause increases in stream salinity in forest with substantial accumulations of salt in the soil.

The simultaneous increases in water production and wood production indicate an increase in water use efficiency at the catchment scale. This increase in water use efficiency is probably caused by the reduction in competition and because the relatively young and vigorous retained trees which have a greater increase in water use efficiency than the older trees when released from competition.

Chapter 1: General Introduction

The majority of Western Australia is arid or semi-arid and only six per cent of the State is forested. Streamflow from this forested area comprises most of the water supply to the south-west region. The population of Western Australia is approximately 1.3 million of which nearly 90 per cent are in the south west and over one million reside in the city of Perth. Catchments in the northern jarrah (*Eucalyptus marginata* Donn. ex Sm.) forest currently account for about 67 per cent of Perth's public water supply. The rate of increase of water usage in the Perth metropolitan area is currently six per cent yr^{-1} and this is necessitating the development of new more distant water sources. The development of these new sources will become increasingly costly as the State water usage grows.

The jarrah forest is a plant community of moderately tall trees (to 35 m) located in the south-western corner of Western Australia. It occurs from about Gingin in the north to Albany in south. The forest is more or less west of a line from near Gingin, Northam, Williams and Albany (Abbott and Loneragan 1986). The northern jarrah forest covers essentially the northern portion of this area, and has the Preston River as its southern boundary (Figure 1.1). It occupies an area of 10,500 km^2 (Havel 1975).

The jarrah forest has traditionally been actively managed for wood production alone. There is a continuing demand for a range of jarrah wood products, particularly the high quality furniture grade wood. However, there is a need to manage the forest for a multiplicity of uses. The two most important land uses over the greater part of the northern jarrah forest are water production and wood production.

Shea *et al.* (1975) suggested that one option for increasing the capacity of the metropolitan water supply system is to reduce forest density in the northern jarrah forest water supply catchments. Streamflow from the northern jarrah forest catchments is, on average, only nine per cent of rainfall. The remaining rainfall evaporates back to the atmosphere. Transpiration typically returns 60 to 80 per cent of the annual precipitation to the atmosphere. Interception of rainfall by vegetation accounts for another 10 to 20 per cent.

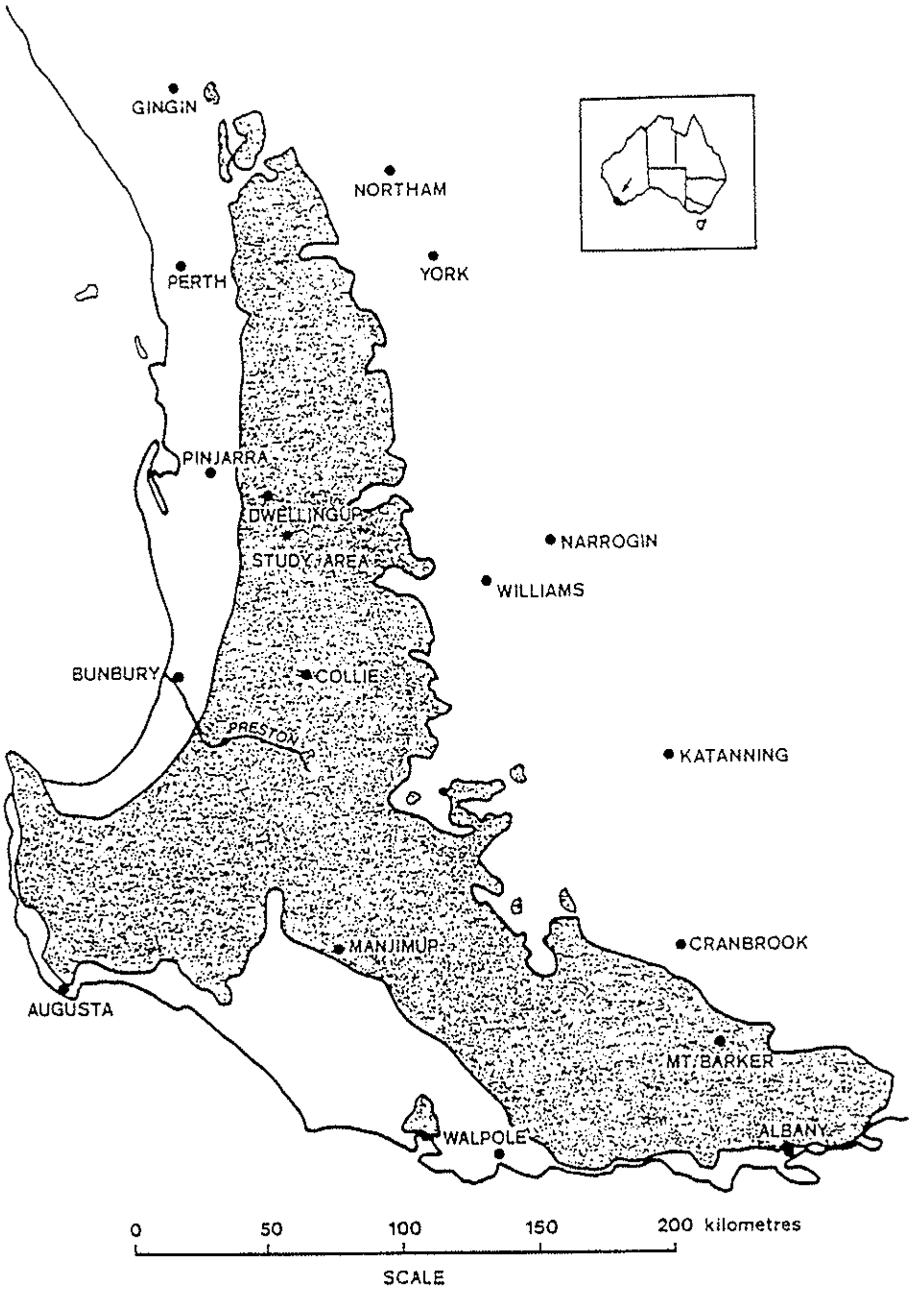

Figure 1.1: Location and extent of the jarrah forest.

Evaporation from the soil surface and organic litter generally removes less than 10 per cent, and streamflow accounts for between 0 and 20 per cent of the annual precipitation (Borg *et al.* 1987a, Schofield *et al.* 1988).

Thinning of the forest reduces its leaf area and therefore reduces interception and transpiration for a period. Streamflow should therefore increase for a period. Many catchment experiments around the world have shown this to be the case (Bosch and Hewlett 1982). However, because of the deep soils and mediterranean climate in the jarrah forest, it is possible that the increased net rainfall will be transpired over the summer drought period. This transpiration could be by both the retained overstorey and understorey. If this is the case, there will be little increase in streamflow and groundwater level following thinning.

As will be discussed in Chapter 2, in spite of the fact that thinning reduces leaf area, the thinning of even-aged stands to an appropriate density generally results in stand growth being maintained. There is even some evidence to suggest that thinning of uneven-aged stands can increase stand growth. However, as there is generally a positive linear relationship between leaf area and growth, it may not be possible to simultaneously increase both streamflow and wood production by thinning.

The objective of this thesis is to test the hypothesis that the thinning of an uneven-aged jarrah forest catchment will simultaneously increase both water and wood production.

The climate of the northern jarrah forest is typically mediterranean. Rainfall ranges from nearly 1400 mm in the west to 700 mm in the east. Rainfall is strongly seasonal, most falling during the winter months of June, July and August. The ratio of winter (April to October) to summer (November to March) rainfall is about 6:1. The south-western portion of the northern jarrah forest experiences 20 days per annum with temperatures exceeding 32.5° C; this ranges to over 40 days in the north-east of the area (Havel 1975). Annual pan evaporation is greater than annual rainfall, and ranges from about 1400 mm in the south-west to 2000 mm in the north-east. Daily potential evaporation rates in excess of 10 mm are common in summer (Shea *et al.* 1978). About 80 per cent of pan evaporation occurs during the six months from November to April. Pan evaporation exceeds rainfall for the seven months from October to April (Loh *et al.* 1984).

The hydrology of the northern jarrah forest is unusual, the feature being that evapotranspiration dominates the water balance. Consequently, there is little streamflow from the moderate rainfall. The high evapotranspiration is attributed to the high evaporative potential of the atmosphere and the large soil water storage capacity which as a result of the very deep soil profiles jarrah is adapted to exploit. The high evaporative potential of the atmosphere drives this exploitation of soil water (Shea *et al.* 1975; Doley 1967; Dell *et al.* 1983; Colquhoun *et al.* 1984). There is also a climatic gradient across the forest. From west to east across the forest, rainfall diminishes from nearly 1400 mm to 700 mm, evaporative potential increases from 1600 mm to 1800 mm, streamflow decreases, saltfall in rainfall decreases from about 100 kg Cl^{-1} ha^{-1} yr^{-1} to 20 kg Cl^{-1} ha^{-1} yr^{-1} and saltflow in streamflow decreases. Additionally there are also changes in landform with the valleys becoming progressively less incised and the slopes more moderate from west to east (Shea *et al.* 1975;

Hingston and Gailitis 1976; McArthur *et al.* 1977). In the higher rainfall western portion of the forest, there is sufficient rainfall and steep enough topography to keep the soil leached of salt. However, in the lower rainfall forest to the east, this is not the case. Virtually all rainfall is evapotranspired, resulting in substantial accumulations of salt in the soil (Dimmock *et al.* 1974; Johnston 1981; Stokes *et al.* 1980). In this lower rainfall area there is potential for the mobilization of this soil salt if groundwater recharge increases and raises the groundwater table. An increase in stream salinity would result. This has been well documented for the case following agricultural clearing (Peck and Hurle 1973; Peck and Williamson 1987; Williamson *et al.* 1987).

The jarrah forest is dominated by the jarrah tree. The forest is probably the least mixed eucalypt forest covering such an extensive area. Marri (*Eucalyptus calophylla*) also occupies a large part of this area, as do to a lesser extent, *E. patens*, *E. rudis*, *E. megacarpa*, and *E. wandoo*. *Allocasuarina fraseriana* and *Banksia grandis* are probably the most dominant understorey species. The vegetation superficially appears uniform. More realistically though, it forms a complex multi-dimensional continuum of overstorey and understorey species responding to a number of changing environmental variables (Havel 1975).

Over 100 years of logging has converted the old-growth northern jarrah forest into a forest dominated by relatively young, dense regrowth stands. The proportion of regrowth in any area reflects the logging history. Early uncontrolled logging was concentrated in accessible high quality areas. These areas were often clearfelled and have regenerated to even-aged regrowth stands. Later controlled logging was selective and has given rise to uneven-age stands. Both types of stands are overstocked, exhibiting low growth rates on individual stems and high water use by the whole stand (Stoneman *et al.* 1988a, Schofield *et al.* 1988).

Chapter 2: Literature Review

2.1. Effect of Thinning in Even-Aged Stands on Tree and Stand Growth

2.1.1. Tree growth

There have been a great many studies dealing with the effect of thinning on tree growth. It is quite clear that if the thinning is done properly, then trees will respond with increased growth. Up to the point where trees are growing freely with no competition from their neighbours then the greater the intensity of thinning the greater the growth response. Further thinning will not increase growth further beyond this point (Smith 1962).

2.1.2. Stand growth

Moller (1954) describes some of the European history on theories of the relationship between stand density and stand growth. The earliest theory was developed in Denmark about 1750 when it was believed that stand growth was directly proportional to stocking. The theory was developed for overcut forest, and subsequent research has shown that the theory does have some basis in this case. As early as 1811, Reventlow proposed that thinning would be economically helpful. However, this was not accepted by other foresters for more than 50 years. About the end of the 1800's, the theory swung full circle in Scandanavia and parts of Germany. They believed that stand growth decreased with stand density. This idea had arisen in Denmark at the same time as the development of industrial wood use and the thinning was undertaken to satisfy the needs of the wood industry. The theory was based on the observation that the forest canopy closed again equally quickly after heavy as after light thinning. This was interpreted to mean that the stand had grown the volume removed. Thus, it was believed that the heavily thinned stands had grown more. Results to support this theory were published in 1911 and 1924 by Schwappach and Engler, respectively. In 1930, Gehrhardt published yield tables for German stands which also showed that the greatest stand growth occurred for the heaviest thinnings. However, in 1932 Wiedeman published results that showed that stand growth was independent of stand density over a wide range of stand densities. Moller (1954) also reported similar results. Langsaeter (1941) (as quoted by Smith 1962) proposed that the relationship between stand density and stand growth was similar to that proposed by Wiedeman and Moller with the qualification that stand growth fell at very high stand densities. Assmann (1970) argues there is not a plateau as Langsaeter proposed, but there is a specific density at which a maximum growth occurs.

Basically, there are thus four prevailing theories about the relationship between stand density and stand growth:

(i) That stand growth increases with increasing stand density (as believed in Denmark about 1750) (figure 2.1a).

(ii) That stand growth increases with increasing stand density up to a point. Then there is a plateau where stand growth is independent of stand density (as proposed by Moller) (figure 2.1b).

(iii) That stand growth increases with increasing stand density up to a point. Then there is a plateau in stand growth over a wide range of stand densities, followed by a fall in stand growth with very high stand densities (the Langsaeter curve) (figure 2.1c).

(iv) That the relationship is similar to the Langsaeter curve except that the wide plateau does not occur and there is a definite peak in the curve

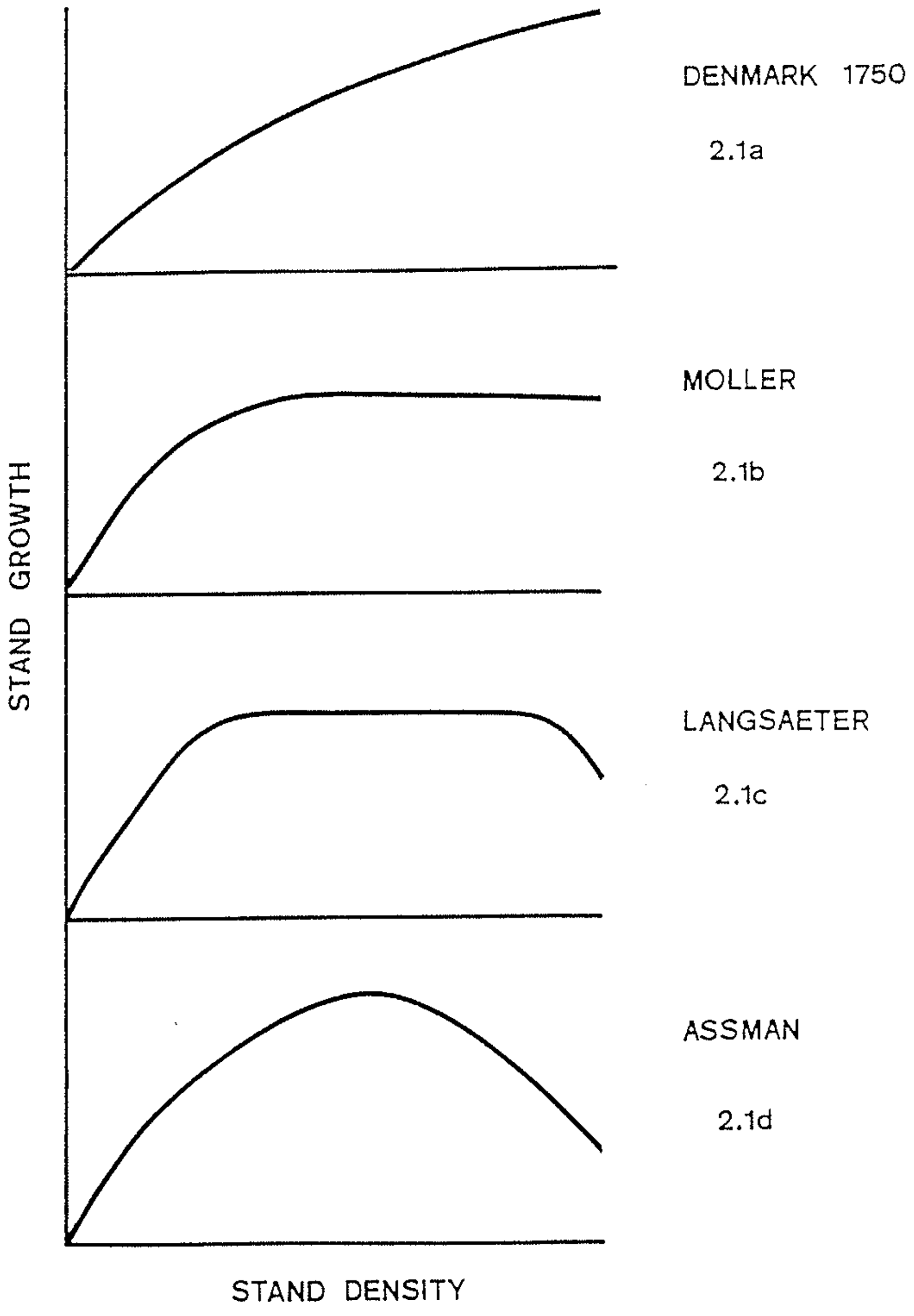

Figure 2.1: Relationships between stand growth and stand density.

(as proposed by Assmann) (figure 2.1d).

Whilst there is a mass of literature dealing with this subject, much of it is based on poorly designed experiments. There is limited literature based on experiments of sound design and statistical analysis with the results presented so that they can be examined with respect to conformity to the relationships above. This literature is reviewed below in relation to the four proposed relationships (curves) above.

A number of authors have reported that stand growth is greatest at highest stand density (Dahms 1971, Van Laar 1973, Cochran 1979, Seidel 1982, Xydias *et al.* 1983, Oliver and Murray 1983, Harvey 1983, Seidel 1986). However, these results should be interpreted with some caution. The study by Harvey (1983) clearly showed that stand growth increased with increasing stand density. However, this was only the case in the first 10 years following the thinning of the young *Pinus patula* stand. A plateau effect emerged later. Xydias *et al.*'s (1983) study was for a young stand, and the control stocking level was also not at a particularly high level (1600 stems ha^{-1}). Low control stocking levels (560 stems ha^{-1}) could also have influenced the results of Cochran (1979). Dahms (1971), Cochran (1979), Siedel (1982), Van Laar (1973) and Oliver and Murray (1983) all found volume growth but not basal area growth reduced by reducing stand density. In some cases the volume growth data showed considerable scatter and could well have been interpreted to be a Moller type curve e.g. Seidel (1986).

The Moller type relationship (figure 2.1b) is the most commonly reported case for gross (i.e. not counting mortality as negative growth) stand growth (Dale 1968, Dahms 1971, Dahms 1973, Cochran 1979, Siedel 1982, Williamson 1982, Borman and Gordon 1984, Hoyer and Swanzy 1986). Inions and Breidahl (in prep.) found the Moller type relationship in the first year after thinning *Eucalyptus diversicolor*. Bevege (1972) and Ronco *et al* (1985) also found this relationship for net stand growth.

A number of authors have shown the Langsaeter type relationship for net stand growth (Williamson 1982, Dale 1968, Dahms 1973). This is due to high mortality in unthinned and lightly thinned stands. However, the only authors to show a Langsaeter or Assman type relationship for gross stand growth have been Abbott and Loneragan (1983) and Stoneman *et al.* (1988a) for jarrah and Horne and Robinson (1987) for *Callitris glaucophylla*. Whilst a curve with a definite peak could fit the results of Abbott and Loneragan (1983) and Stoneman *et al.* (1988a), basal area increment was found to be essentially independent of stand basal area under bark over the range of 8-17 m^2 ha^{-1}. Therefore, the Langsaeter relationship is most valid for these data. Horne and Robinson (1987) also show a Langsaeter curve, although the statistical significance of the drop in stand growth with increasing stand density may be doubtful.

Whilst Assman did have considerable information which fitted his proposed relationship, none of the experimental designs were sound and no statistical analysis shown. Inions and Breidahl (in prep.) have been the only authors to show a clear peak in the response curve. This was for a 12-year-old *Eucalyptus diversicolor* stand in the second year following thinning.

The relationship between stand growth and stand density should not be peculiar to forest stands. A review of the agricultural, botanical and horticultural literature is therefore appropriate. These sciences have the advantage that variability in other factors affecting growth can be much more readily controlled, the life cycle is much shorter and results are thus gained much more quickly. Harper (1977) effectively reviews this literature and concludes the relationship is of the Moller type. The plateau only emerges after enough time has elapsed (figure 2.2). This is termed "the law of constant final yield" (Kira *et al.* 1953).

However, the growth of forest stands can be significantly different to that of annual agricultural crops. For example, the 'locked up' condition that some forest stands experience has not been reported for agricultural species. In conclusion, it seems that the Moller type curve is appropriate for most forest stands i.e. thinning of an even-aged stand is not expected to lead to an increase in stand growth. However, the Langsaeter curve is found in some stands which do not readily self thin e.g. jarrah pole stands.

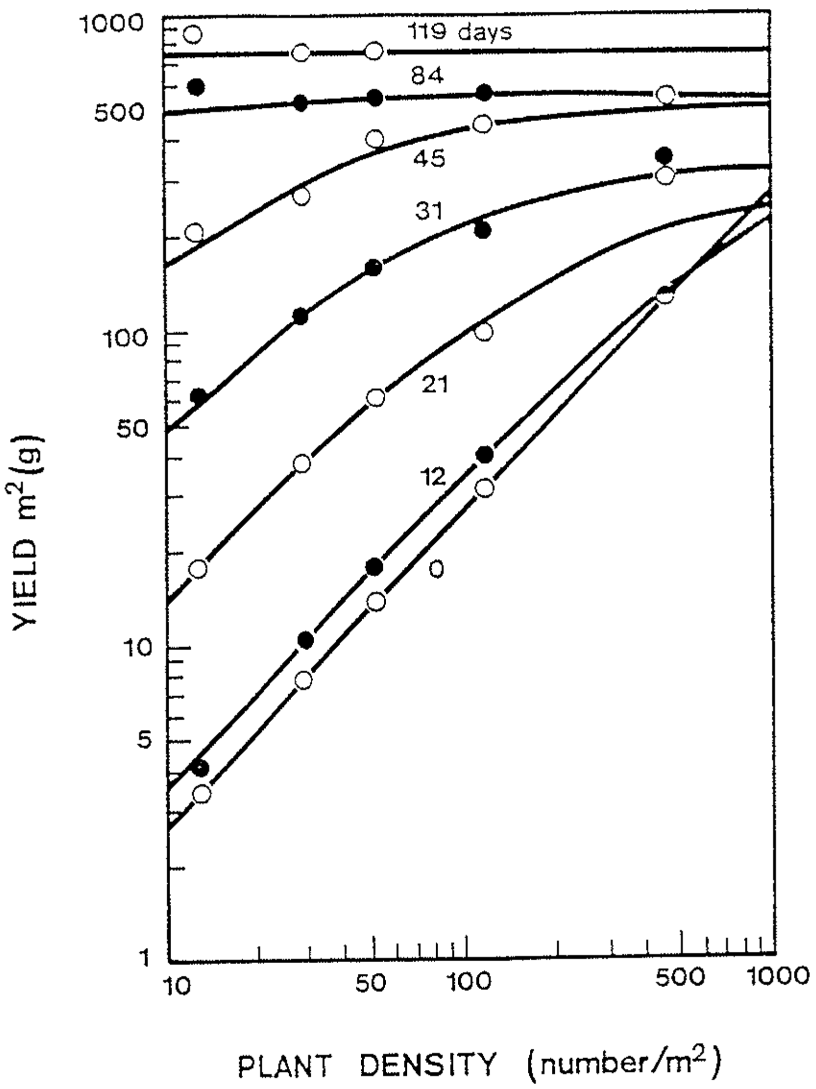

Figure 2.2: The relationship between yield of corn, sowing density and days after sowing (from Harper 1979).

2.2. Effect of Thinning in Uneven-Aged Stands on Tree and Stand Growth

2.2.1. Tree growth

Results from the literature show that there is a favorable tree growth response to thinning in uneven-aged stands. However, there are differences in the patterns of response that occur. McLemore (1983) found that suppressed trees in a mixed pine-hardwood stand responded to release from competition. The healthiest and largest individuals responded most (only trees up to 23 cm diameter at breast height were included in the study). Eyre and Zillgitt (1953) found that all size classes responded to partial cuts with the largest diameter growth response occurring in the smaller size classes. Henry (1960) reported that thinning of mixed *Eucalyptus maculata - E. siderophloia* forest increased average diameter growth by a factor of between two and six. Squire and Edgar (1975) found that basal area increment of *E. obliqua* regrowth stems in a mixed age stand approximately doubled in response to individual tree release. However, they only studied trees up to 30 cm diameter at breast height. Kellas *et al.* (1982) studied the effect of releasing *E.*

sideroxylon from competition. When overwood (> 20 cm diameter at breast height) was removed without a reduction in regrowth competition there was an increase in basal area increment of regrowth stems. When regrowth competition was reduced as well, there was a further increase in basal area increment of regrowth stems. Basal area increment of these most heavily released stems was about double that of unreleased stems. When overwood was not thinned and regrowth was thinned, there was not a significant response in growth of the regrowth stems. Opie (1969) showed that old-growth *E. camaldulensis* influenced the growth of regrowth within a radius of twice the radius of the tree crown. Rotheram (1983) showed old-growth karri had a similar level of influence on regrowth karri. Incoll (1979) has also shown that old-growth *E. sieberii* affect the growth of nearby regrowth.

In conclusion, a growth response by the residual trees in an uneven-aged stand following thinning can be expected. The pattern of the response will probably depend to a large extent on the stand structure both before and after treatment.

2.2.2. Stand growth

The literature on the effect of thinning on stand growth of uneven-aged stands is relatively meagre. However, some of the results seem to be in conflict with the basic principle established for even-aged stands i.e. that stand growth can generally not be increased by thinning. Henry (1960) reported that thinning of uneven-aged cypress pine stands led to a doubling of stand basal area increment. Kellas *et al.* (1982) estimated that the stand basal area increment of the regrowth component of a *E. sideroxylon* stand could be increased by over 50 per cent by thinning the overwood. Henry (1960) reported that thinning of an uneven-aged rainforest increased stand basal area increment by 300 per cent. Eyre and Zillgitt (1953) found stand basal area increment to increase by between 15 per cent and 65 per cent following partial cuts. However, in a mixed *E. maculata - E. siderophloia* stand, thinning did not significantly affect stand basal area increment (Henry 1960).

In conclusion, it seems that thinning of uneven-aged stands may lead to an increase in stand growth. However, the response will probably depend to a large extent on the stand structure both before and after treatment.

2.3. Effect of Thinning on Merchantable Volume Growth

Thinning either decreases, has no effect, or increases merchantable volume growth of a stand. This variable response can be attributed to the interaction of a number of factors, including:

(i) The `time period' between the thinning and the remeasurement. If the period is very short, the trees will not have advanced into the next merchantability class. If the period is very long, all trees in both thinned and unthinned stands will have advanced into the large size classes.

(ii) The `growth rate' of the trees. Faster growing trees advance more rapidly into higher merchantability classes.

(iii) The `size class distribution' of the unthinned and thinned stands. Again this will affect the time that different portions of the stand take to reach merchantability limits.

(iv) The `intensity of thinning'. This factor will have an effect in two ways. Firstly, on the growth rate of the trees. Secondly, on the growth rate of the stand. If the trees are growing much faster after thinning, they will advance much more rapidly into higher merchantability classes. Where thinning is very heavy in even-aged stands merchantable volume growth will be reduced. In uneven-aged stands where the stand growth is increased by thinning, this increases merchantable volume growth.

(v) The `proportion of degraded trees' in the stands and how effectively thinning removes these degraded trees. Thinning increases merchantable growth by concentrating growth onto useful trees.

It is very difficult to distinguish between the effects of 'time period', 'growth rate' and 'size class distribution' from the results in the literature. These three factors are grouped in the following discussion.

Results from the literature illustrate the effects of these factors for both even-aged and uneven-aged stands.

2.3.1. Even-aged stands

Many authors have reported an increase in merchantable volume growth following thinning. In the cases of Johnstone (1981), Siedel (1982) and Bella and De Franceschi (1974) the increase is attributed to a combination of 'time period', 'growth rate' and 'size class distribution'. For Wallace and Podger (1959) the 'proportion of degraded trees' may also have contributed. For Harvey (1983), and Shepperd and Forrest (1973), the 'intensity of thinning' was also a factor.

Other literature, however, reports no effect or a reduction in merchantable volume growth following thinning. Opie *et al.* (1978), Harvey (1983) and Shepperd and Forrest (1973) reported some instances where thinning had no effect on merchantable volume growth. This is attributable to a combination of 'time period', 'growth rate' and 'size class distribution'. In some papers a reduction in merchantable volume growth was found (Opie *et al.* 1978, Xydias *et al.* 1983, Shepperd and Forrest 1973). A combination of factors are judged to be causative. These include the 'time period', 'growth rate', 'size class distribution' and 'intensity of thinning'.

2.3.2. Uneven-aged stands

Several studies in uneven-aged stands have reported an increase in merchantable volume growth following thinning. In the cases of mixed *E. maculata-E. siderophloia* forest (Curtin 1970; Henry 1960) this was attributed to the 'proportion of degraded trees'. In the cases of a cypress pine stand and a rainforest stand (Henry 1960) this was attributable to a combination of an increase in stand growth due to the `intensity of thinning' and the 'proportion of degraded trees'. Florence (1970), Florence *et al.* (1970) and Florence and Phillis (1971) have also argued that productivity of uneven-aged eucalypt stands is increased by removing the useless growing stock. This growth is then concentrated onto trees with little or no degrade.

No studies have been cited for uneven-aged stands where thinning either had no effect or reduced stand merchantable volume growth.

2.4. Previous Studies on the Effect of Thinning on the Growth of Jarrah

2.4.1. Stump coppice

Chandler (1939) reported on the effect of thinning five-year-old stump coppice resulting from regeneration treatment in 1932 in Sawyer block about 80 km north of Dwellingup (location shown as site 1 on figure 2.3). Bednall (1942), and Abbott and Loneragan (1982) have also reported on this experiment. Thinning to one or two stems per clump had no effect on diameter growth. The lack of difference between treatments in the early years may be due to the extensive root system of the stump. This would have the capacity to supply nutrients and moisture to all coppice shoots. Abbott and Loneragan (1982) attributed the lack of a difference in growth rate between thinning treatments to there being usually only one leading coppice shoot per stump. They argue that the remaining coppice shoots are dominated by the dominant shoot and have little effect on the growth rate of the dominant shoot.

However, a lack of response of dominant stems at this young age is not unusual. Similar results

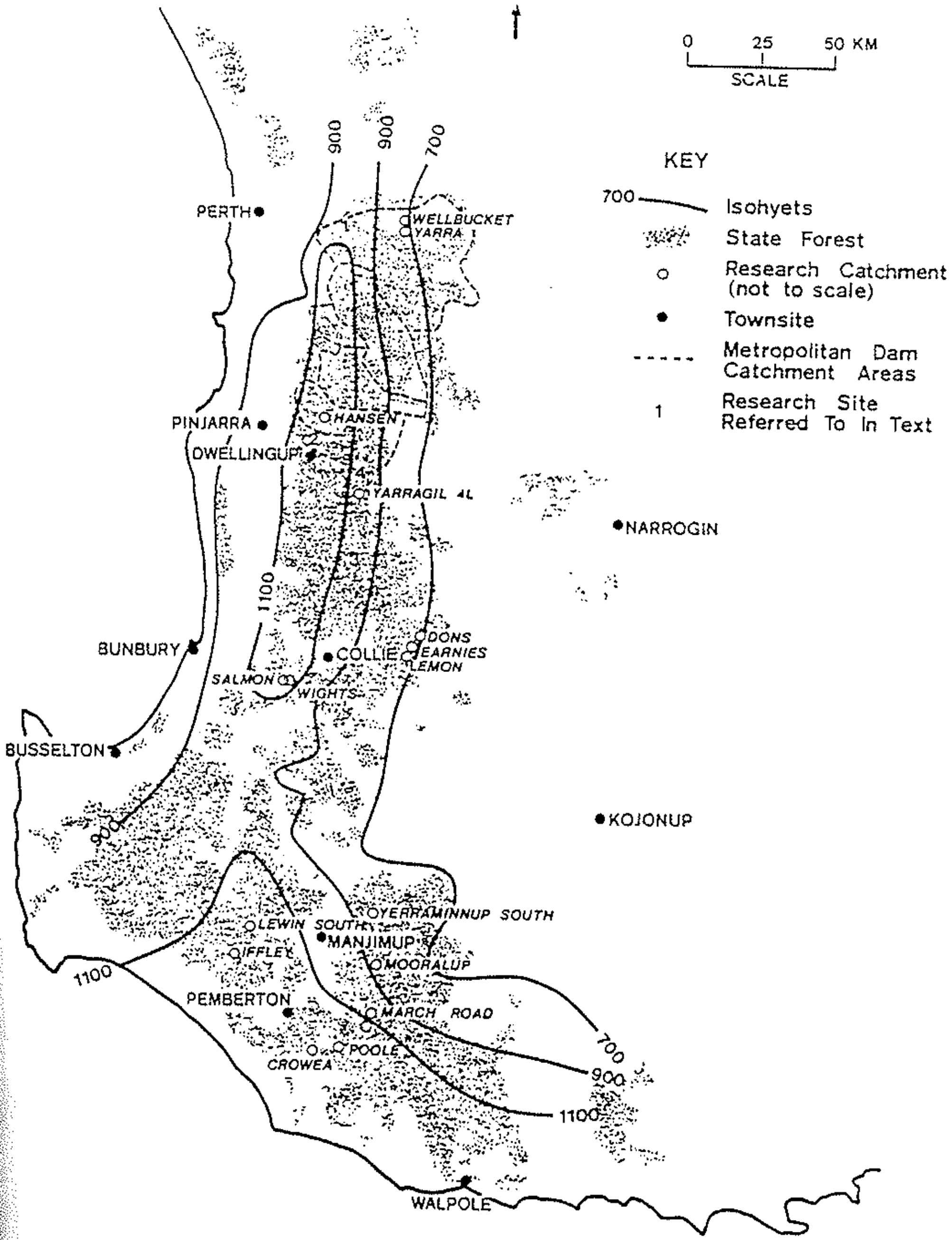

Figure 2.3: Research catchments and sites in the jarrah forest.

were also obtained from saplings (see section 2.4.2). At older ages and with a thorough thinning of the whole stand, a growth response similar to poles should occur.

2.4.2. Saplings (< 15 cm diameter at breast height over bark)

Abbott and Loneragan (1983) reported the results of thinning a 15-year-old sapling stand in Holyoake block near Dwellingup (site 2 on figure 2.3). Stand basal area increment was less on the two thinned plots than on the unthinned plot. Growth rates of the regrowth stems > 22.5 cm diameter at breast height, and of the largest 100 regrowth stems ha^{-1} were compared across treatments. A degree of self thinning was clear in the unthinned plot.

A second thinning experiment in a sapling stand was in a 12-year-old stand in Chalk block about 40 km south-south-east of Dwellingup (site 3 on figure 2.3). Results are reported by Stoneman *et al.* (1988a). The plots were thinned in 1967. The growth data are for the period 1967-84. There were four thinning intensities, nominally 250, 375, and 500 stems ha^{-1}, and unthinned plots ranged from

1400 to 3400 stems ha^{-1}. Thinning reduced stand basal area increment (figure 2.4). Average diameter growth per plot increased nine-fold from 0.5 mm yr^{-1} at 3400 stems ha^{-1}, to 4.5 mm yr^{-1} at 200 stems ha^{-1}. However, this is a biased measure of growth response. Only the best trees remain in the thinned plots, whilst all the small, slow growing trees remain in the unthinned plots, and, therefore, lower the average diameter growth. The fastest growing 100 stems ha^{-1} increased diameter growth from 3.1 mm yr^{-1} (at 3400 stems ha^{-1}), to 3.8 mm yr^{-1} (at 1500 stems ha^{-1}), and 5.3 mm yr^{-1} (at 200 stems ha^{-1}). The fastest growing trees responded most to thinning. There was virtually no response on trees other than the fastest growing 300 stems ha^{-1}. Mortality was greater in the more densely stocked stands.

2.4.3. Poles (15-45 cm diameter at breast height over bark)

Abbott and Loneragan (1983) reported the results of a number of experiments dealing with the effect of thinning pole stands. These all showed substantial increases in average diameter growths. There were no reductions in stand basal area

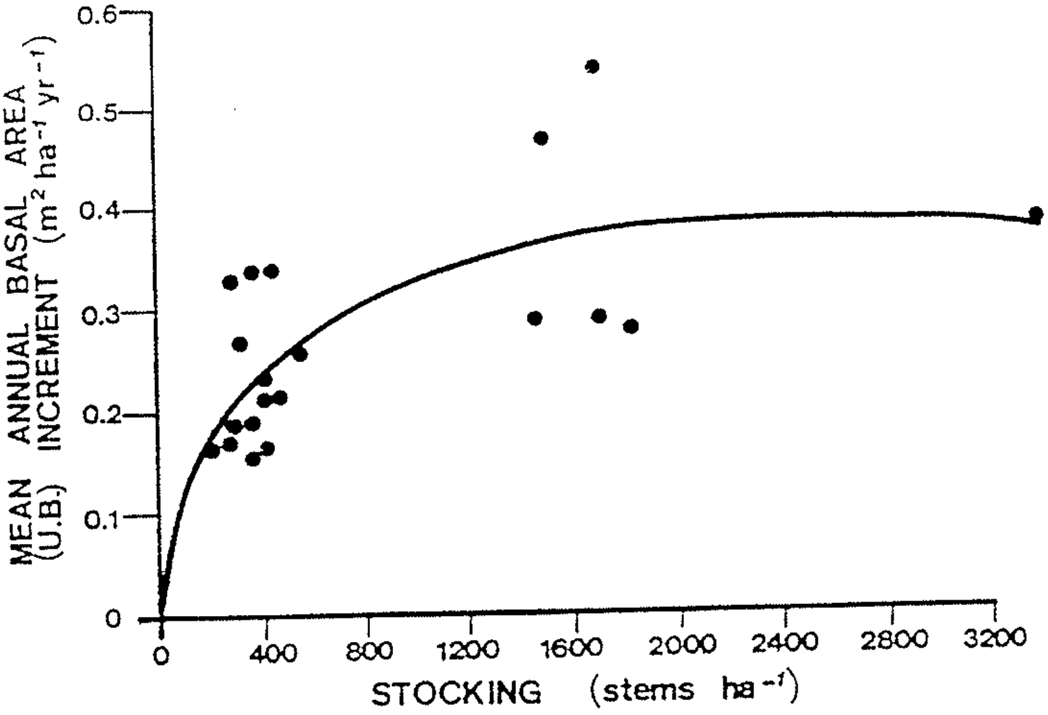

Figure 2.4: The effect of thinning a 12-year-old jarrah sapling stand on stand basal area increment (from Stoneman *et al.* 1988a).

increment until stands were thinned to below 30 per cent of initial basal area.

Further work on the Inglehope block experiment which is about 12 km east-south-east of Dwellingup (one of the experiments reported on by Abbott and Loneragan 1983)(site 4 on figure 2.3), over a longer period has yielded more information (Stoneman *et al.* 1988a). Stand basal area increment was found to be relatively independent of stand density over the basal area over bark range of 10-25 m^2 ha^{-1} (figure 2.5). However stand basal area increment reduced with basal area over bark $<$ 10 m^2 ha^{-1} or $>$ 25 m^2 ha^{-1}. Average diameter growth increased nearly seven-fold from 0.6 mm yr^{-1} for unthinned stands at 30 m^2 ha^{-1}, to 4.0 mm yr^{-1} at 9 m^2 ha^{-1} basal area over bark. This is again a very biased measure of the effect of thinning as the diameter growth of the crop trees (200 stems ha^{-1}) only doubled. The fastest growing 50 stems ha^{-1} increased their growth rate from 2.5 mm yr^{-1} to 5.3 mm yr^{-1}. The second fastest growing 50 stems ha^{-1} increased their growth rate from 2.1 mm yr^{-1} to 4.0 mm yr^{-1}. The fastest growing trees were again the ones which responded most to thinning. There was little response on trees other than the fastest growing 300 stems ha^{-1}.

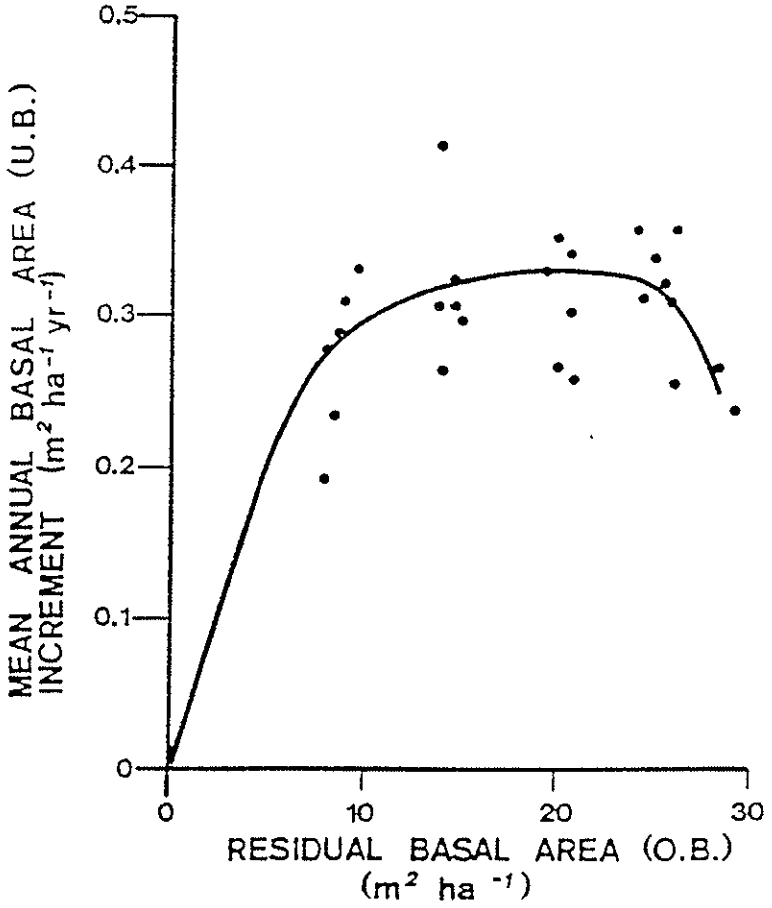

Figure 2.5: The effect of thinning a 40-year-old jarrah pole stand on stand basal area increment (from Stoneman *et al.* 1988a).

However, the fastest growing trees are not always the trees which respond most to thinning. For example, Horne (pers. comm.) found that the small slower growing trees were the ones that responded most to thinning for *E. pilularis* on a low quality site, whereas on a high quality site the fastest growing trees were the ones that responded most.

The method described by Horne *et al.* (1986) was used by Stoneman *et al.* (1988a) to determine the components of the total stand increment (figure 2.6). These components are:

(i) The base increment - which would accrue to any selected subset of trees, irrespective of thinning. The curve is fitted to data from the unthinned stands.

(ii) The thinning response increment - accruing to any selected subset of trees remaining after thinning as a direct consequence of the reduction in competition. The response increment is essentially the difference between the base increment and the total increment.

The base increment curve shows the fastest growing 130 stems ha^{-1} i.e. 10 per cent of the trees, accrue 45 per cent of the stand increment.

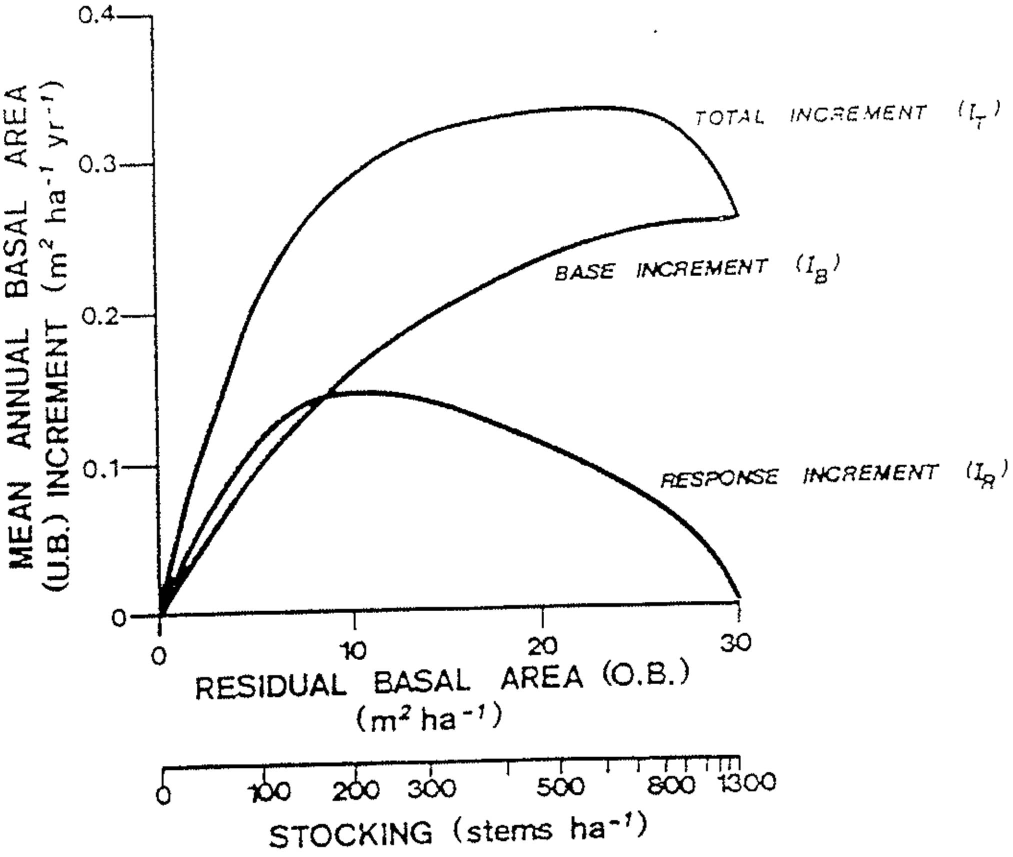

Figure 2.6: The effect of thinning a 40-year-old jarrah pole stand on the basal area thinning response increment, the base increment and the total increment.

$$I_T = I_B + I_R$$

where I_T = total stand increment

I_B = the base increment that would accrue to the selected trees irrespective of thinning

I_R = the thinning response increment accruing to the selected trees as a direct consequence of the reduction in competition.

(from Stoneman *et al.* 1988a)

The fastest growing 260 stems ha^{-1} i.e. 20 per cent of the trees, accrue 60 per cent of the stand increment. The fastest growing 650 stems ha^{-1} i.e. 50 per cent of the trees, accrue 97 per cent of the stand increment. The slowest growing 600 or 700 stems ha^{-1} accrue virtually no increment at all. They merely survive, whilst using the sites resources of light, water and nutrients. This base increment curve thus shows that faster growing trees in the unthinned stand put on a disproportionally large amount of the stand growth. Horne *et al.* (1986) also assert that the peak in the thinning response increment curve helps to identify the edge of the plateau in the total increment curve. This peak is at just less than 10 m^2 ha^{-1} basal area over bark.

2.4.4. Piles and trees (> 45 cm diameter at breast height over bark)

No information is available on the response of piles and trees to thinning.

2.4.5. Summary of the response of jarrah to thinning

Two of the three growth stages of jarrah on which research has been done to test the effect of thinning have shown increases in diameter growth viz. saplings and poles. In the sapling stand thinning below 1500 stems ha^{-1} led to a reduction in stand growth. In the pole stand two-thirds of the stand basal area or nine-tenths of the stocking could be removed before there was a reduction in stand growth. The relationship between stand growth and stand density for jarrah pole stands is unusual in that it is the only case which has convincingly shown stand growth to decline at high stand densities i.e. the Langsaeter type relationship. This is a reflection of the persistence of the species at this growth stage and its inability to self thin.

2.5. The Effects of Forest Density Reduction on the Water Balance

Some of the following information has been reported by Stoneman and Schofield (1989).

2.5.1. The water balance

The water balance can be written in the following form:

$$P = E_t + E_i \pm \Delta S \pm \Delta G + W$$

where P is rainfall, E_t is transpiration, E_i is interception, ΔS is the change in soil water, ΔG is the change in groundwater and W is streamflow. Interception can be further broken down into its component parts,viz.

$$E_i = P - T_f - S_f$$

where T_f is throughfall and S_f is stemflow.

2.5.2. Transpiration (E_t)

There are very few studies in the literature specifically dealing with the effect of thinning on tree or stand transpiration. Black *et al.* (1980) found that in a 22-year-old Douglas fir stand the effect of thinning was largely negated by understorey transpiration. The transpiration rate of individual trees in the thinned stand was very similar to that of individual trees in the unthinned stand, even though the thinned stand was at half the stand density. The lack of a significant difference in tree transpiration rate can be accounted for by the fact that the thinned stand contained a salal understorey which consumed about half of the extractable soil water. Whitehead *et al.* (1984) found that transpiration from a thinned *Pinus sylvestrus* stand was less than from an unthinned stand. The reduction in transpiration was in proportion to the reduction in leaf area index. They also found stomatal conductance to be lower in the thinned stand. Soil moisture was not limiting and there was no relationship between conductance and soil moisture.

The conceptual model of Jarvis (1975) is a useful way of considering the effect of stand thinning on transpiration (figure 2.7). He argues that a thinned stand will compensate for the reduction in leaf area that thinning imposes. If half the leaf area is removed, the total stem resistance to water flow will double, individual crowns will absorb more radiation, stand transpiration will fall, but flow within the individual stems will increase, and needle water potential will be lowered. The stand will then tend to regrow towards the unthinned leaf area, thereby doubling leaf area per tree. Transpiration

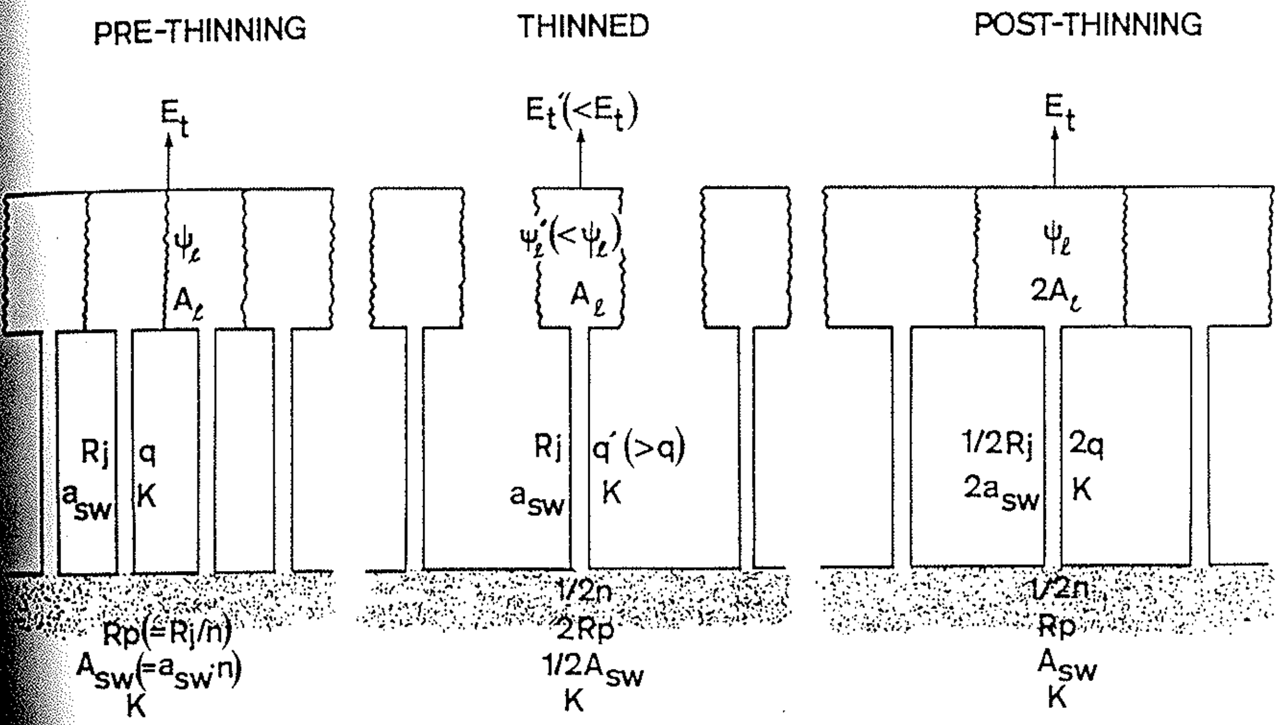

Figure 2.7: Change in transpiration rate (E_t), foliage area (A_l), sapwood basal area (A_{sw}), foliage water potential (ψ_l), and resistance in the pathway between soil and canopy (R_p) following thinning. q, a_{sw}, and R_j refer to the transpiration flux, sapwood cross-sectional area, and stem resistance per unit area in n trees, respectively. K is the permeability for the stand and for an average individual tree (after Jarvis 1975).

will increase back to unthinned levels, flow of water within each tree will double and leaf water potential will return to unthinned levels. Therefore, adverse low water potentials are avoided, and total stem resistance to water flow will return back to unthinned levels. In the stands studied by Whitehead *et al.* (1984) where thinning had taken place 14 years previously, the stand water relations had not recovered to prethinning levels.

McNaughton and Jarvis (1983) argue that transpiration rate from a forest is largely determined by vapour pressure deficit and leaf area. Therefore, the transpiration rate after thinning a forest is reduced in proportion to the reduction in leaf area index.

The effect of thinning on tree and stand leaf area was reported by Stoneman and Schofield (1989) for the jarrah thinning experiment in Inglehope block (site 4 on figure 2.3). Various dimensions and characteristics of selected trees from thinned and unthinned areas were measured, including a large sample from this particular stand. The trees were felled, all leaves harvested and tree leaf area measured. Dimensional relationships to predict the leaf area of individual trees as a function of tree diameter were established. These were used to predict stand leaf area for the thinning plots. Stoneman and Schofield (1989) showed that 21 years after the thinning there was still a very substantial reduction in stand leaf area (figure 2.8). Thinning to 10 m^2 ha^{-1} baob resulted in a stand with a leaf area index of 0.90. In comparison, an unthinned stand at 30 m^2 ha^{-1} baob had a leaf area index of 1.90. This represents a net reduction in leaf area index of 53 per cent with a reduction in stand basal area of 67 per cent.

Schofield (pers. comm.) estimated overstorey transpiration of a jarrah forest site to be 35 per cent of rainfall. Assuming transpiration rate is proportional to leaf area index as argued by McNaughton and Jarvis (1983), then overstorey transpiration would be reduced by 18.5 per cent of rainfall 21 years after reducing stand basal area from 30 m^2 ha^{-1} to 10 m^2 ha^{-1}. However, the 18.5 per cent may be an overestimate of the reduction in transpiration because the increased soil water following thinning may result in increased rates of transpiration per unit leaf area in the thinned stands relative to the unthinned stands.

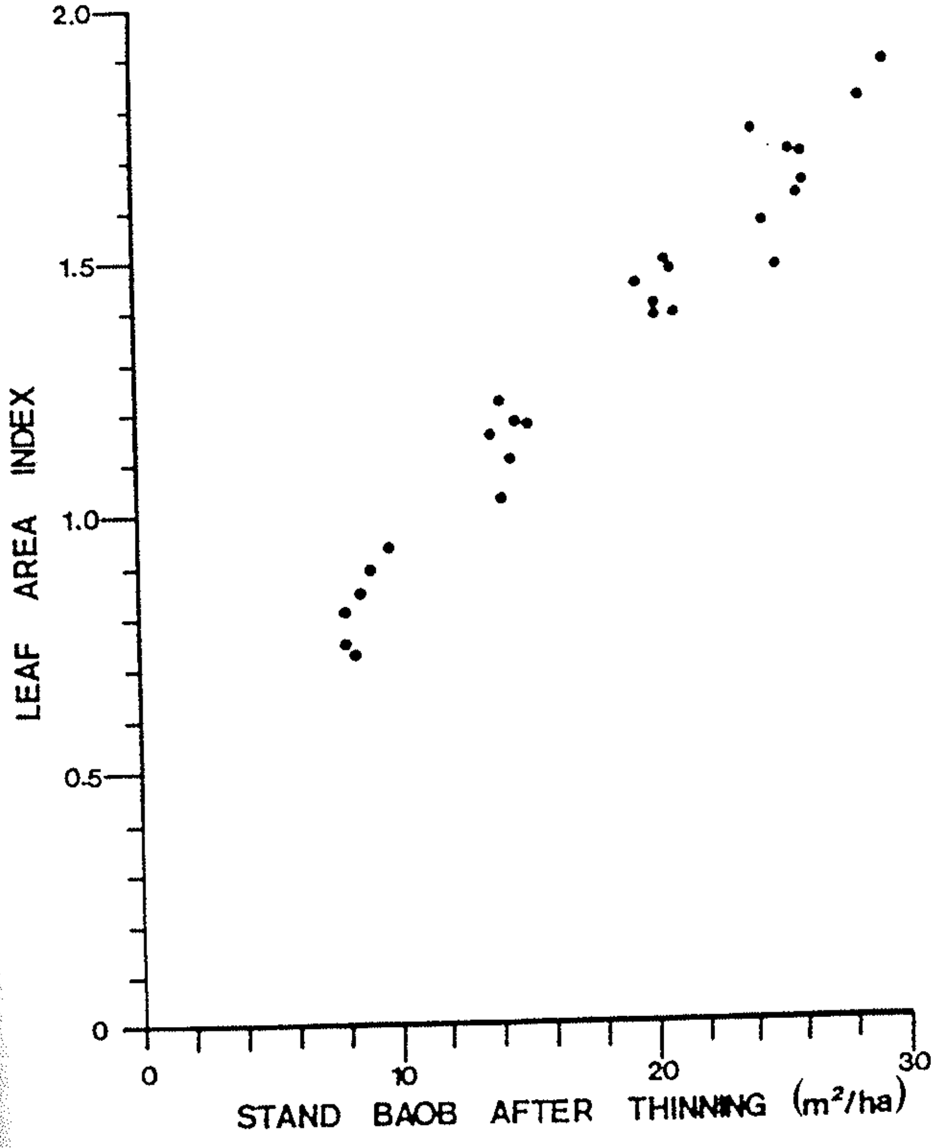

Figure 2.8: Effect of stand basal area over bark on stand leaf area index for a 61-year-old jarrah stand 21 years after thinning (from Stoneman and Schofield 1989). The three stands with the highest baob are unthinned stands.

Nevertheless, the reduction in stand transpiration following thinning clearly creates the potential for substantial increases in streamflow.

2.5.3. Interception (E_i)

There have been a number of reviews and research papers over the years on interception in forests. These have all concluded that interception is, amongst other things, a function of vegetation density (Zinke 1967, Delfs 1967, Rogerson 1967, Blake 1975, Chorley 1978). There are now many models of interception in the literature. These all include vegetation density as an important component (Gash 1979, Massman 1983, Schofield 1984).

In a number of studies, differences in streamflow between forested catchments and cleared catchments have been attributed solely or substantially to the difference in interception (Holmes and Wronski 1981, Holmes and Wronski 1982, Pearce *et al.* (1980).

Regeneration of forest following clearfelling will also have a substantial impact on rainfall interception. Immediately following clearfelling, interception is reduced to a very small proportion of rainfall. As the forest regrows the interception component will increase back towards the level of mature forest, and possibly beyond the mature level at some intermediate point in the life cycle of the stand.

There have been several studies aimed specifically at studying the effect of forest density on interception. Wilm (1943) found that reducing the density of *Pinus contorta* forest reduced interception considerably. Virgin forest with a standing volume of 11800 bd ft acre^{-1} had 31.9 per cent interception. Cutover stands with 8000, 4000 and 2000 bd ft acre^{-1} had 19.9 per cent, 14.9 per cent and 13.5 per cent interception, respectively. A stand with all trees greater than 24 cm diameter at breast height clearcut had only 7.2 per cent interception. Ghosh *et al.* (1980) reported on the effect of thinning *Shorea robusta*. With a reduction in basal area from 24.3 m^2 ha^{-1} (17135 stems ha^{-1}) to 16.7 m^2 ha^{-1} (8684 stems ha^{-1}) interception reduced from 18.0 per cent to 13.1 per cent of rainfall. Butcher (1977) found that thinning of *Pinus pinaster* from 25 m^2 ha^{-1} to 7 m^2 ha^{-1} basal area reduced interception from 26 per cent to 10 per cent. Two stands of 100 per cent canopy cover *Pinus contorta* were logged, one to a 40 per cent canopy cover and the other to a 49 per cent canopy cover. Net rainfall increased by 13.3 per cent and 17.7 per cent, respectively (Goodell 1952).

Stoneman and Schofield (1989) reported on throughfall over the winter of 1985 in a sixty-year-old regrowth jarrah stand which had been thinned to a range of stand densities 20 years previously (site 4 on figure 2.3). The throughfall - basal area (ba) relationship derived for the stand is

$$T_f = 100 - 0.8 \text{ ba}$$

where T_f is measured as a per cent of rainfall. Stoneman and Schofield (1989) also report that the stemflow - basal area relationship is

$$S_f = 0.167 \text{ ba}$$

where S_f is measured as a per cent of rainfall. Using these relationships indicates that interception will decrease linearly from 19 per cent for a stand at 30 m^2 ha^{-1} to 0 per cent at 0 m^2 ha^{-1}. The results above are summarised in table 2.1 and graphed in figure 2.9 which shows that the greater the reduction in forest density then the

Table 2.1: Reports from the literature of reductions in interception of rainfall as a result of reductions in forest density

	Reduction in stand density		Reduction in E_I (% of rainfall)	Reference
Species	(%)	measured as*		
Jarrah	100	BA	19.0	Stoneman & Schofield (1989)
Pinus contorta	32	BF	12.0	Wilm (1943)
Pinus contorta	66	BF	17.0	Wilm (1943)
Pinus contorta	83	BF	18.4	Wilm (1943)
Shorea robusta	31	BA	4.9	Ghosh et al. (1980)
Pinus pinasta	72	BA	16.0	Butcher (1977)
Pinus contorta	60	CC	13.3	Goodell (1952)
Pinus contorta	51	CC	17.7	Goodell (1952)

* BA = basal area

BF = board ft

CC = canopy cover

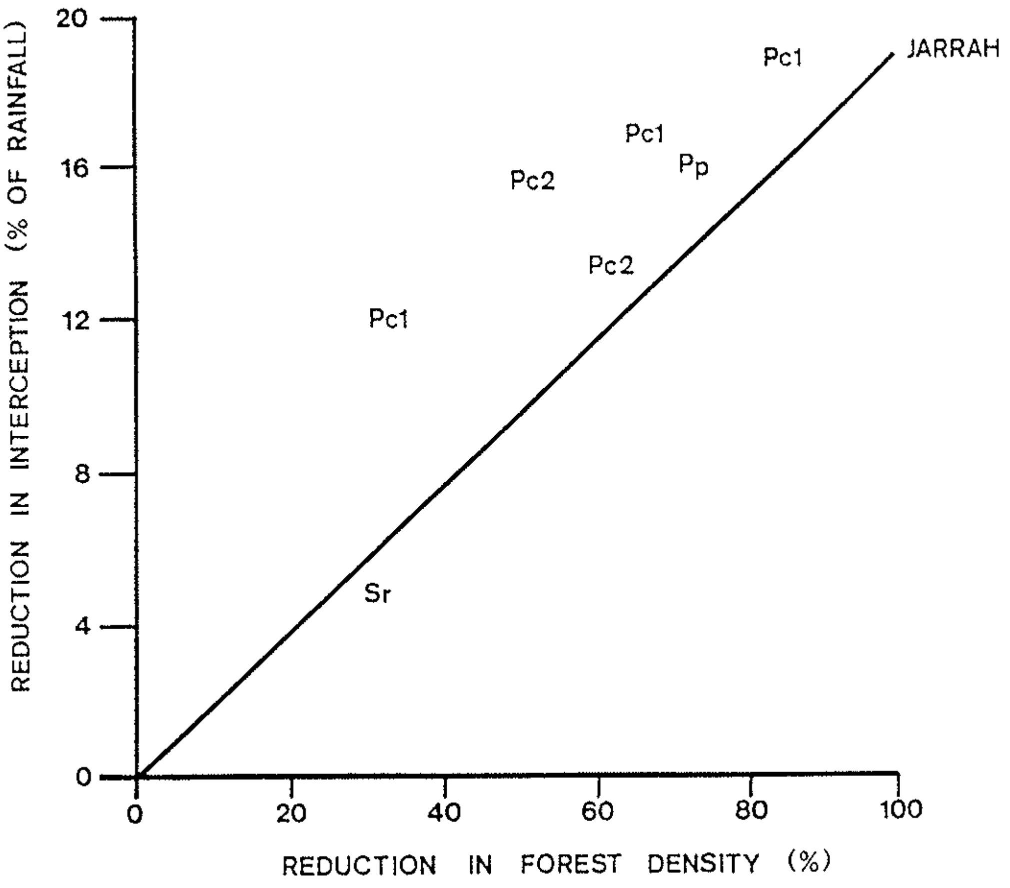

Figure 2.9: Relationship between the reduction in interception and the reduction in forest density for various forest types. Symbols are: Pc1 = Pinus contorta (Wilm 1943), Pc2 = Pinus contorta (Goodell 1952), Pp = Pinus pinaster (Butcher 1977), Sr = Shorea robusta (Ghosh et al. 1980)

greater the reduction in interception. The relationship for jarrah shows a slightly smaller reduction in interception for a given reduction in forest density than for other species. This is possibly a result of the lower leaf area index and thus interception storage capacity of jarrah compared to the other species.

2.5.4. Soil water (S)

Many studies, both in Australia (Butcher 1977, Langford and O'Shaughnessy 1979), and elsewhere (Dahms 1971, Dahms 1973, Zahner and Whitmore 1960, Nnyamah and Black 1977, Schmidt 1978), show that lower stand densities result in reduced rates of soil moisture depletion. Therefore, there are increased levels of soil moisture storage for at least part of the year. One such study over the period 1970-73 was in a jarrah thinning experiment in Inglehope block (Kimber unpublished) (site 4 on figure 2.3). The research plots had been thinned in 1964 to a range of stand densities. Gypsum block observations indicated that soil moisture levels were significantly greater in a thinned plot relative to an unthinned plot throughout most of the year (figure 2.10). This effect was greater at

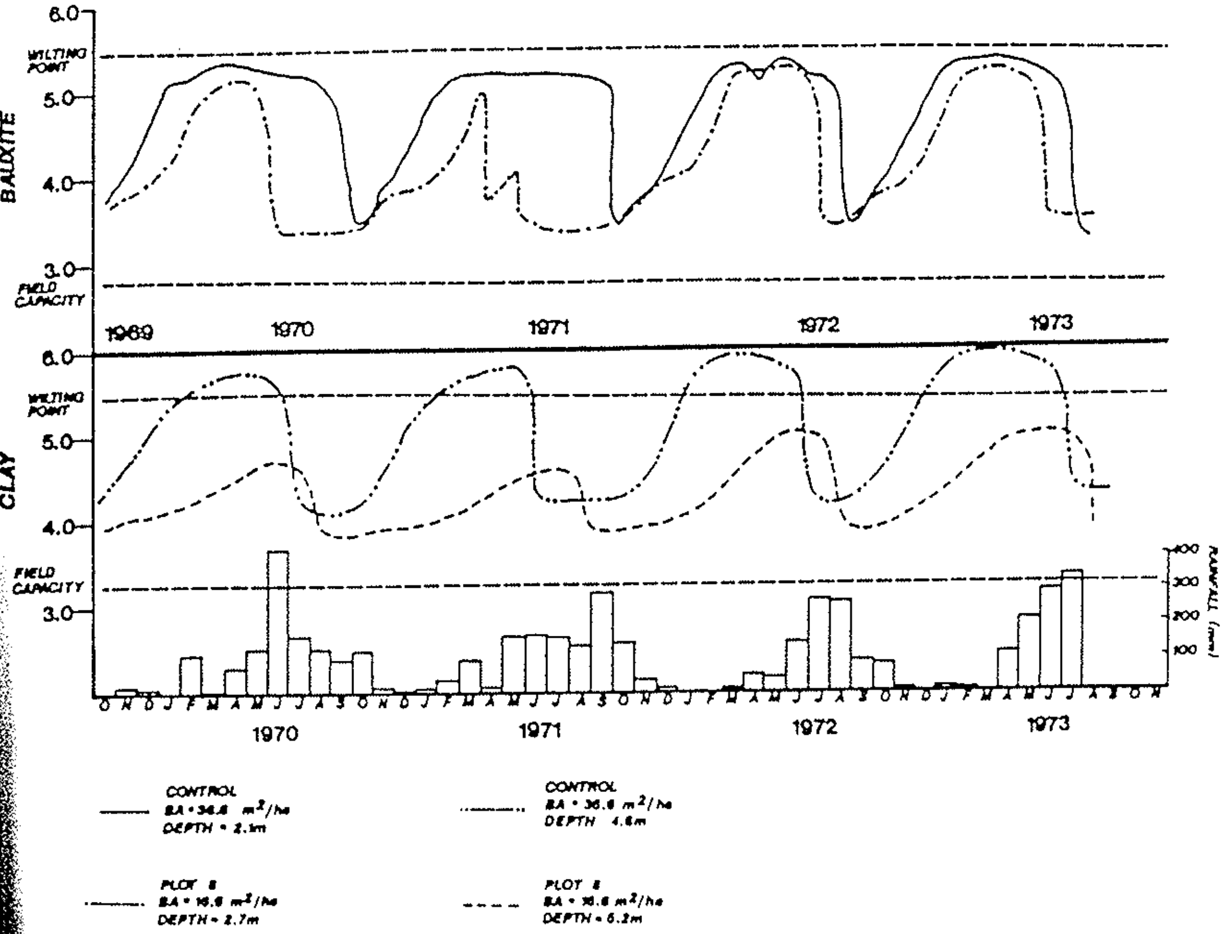

Figure 2.10: The effect of thinning a 40-year-old jarrah pole stand on soil moisture (measured as electrical resistance by gypsum blocks). The stand was thinned in 1964 and the basal areas and soil moisture are for 1970 (from Kimber unpublished).

five m depth than at two m depth. In the unthinned stand, wilting point was approached by the middle of January at two m and by early February at five m. The soil did not approach field capacity until July-August at two m and June-July at five m. In the thinned stand wilting point was only approached at the shallower depth. At five m depth soil moisture levels remained close to field capacity throughout most of the year.

Clearfelling leads to increased soil moisture levels (Dietrick and Meiman 1974, Johnston 1970, Johnston 1975, Klock and Lopushinsky 1980). Following regeneration these levels return towards uncut soil moisture levels (Tew 1969) and possibly below the soil moisture levels of mature stands (Langford and O'Shaughnessy 1979).

Sharma *et al.* (1982) found that agricultural clearing of Wights catchment (see figure 2.3 for location) in the northern jarrah forest increased soil moisture in the upper 6 m of soil profile. Unsaturated soil water content increased by 220 mm after one year and by 279 mm after two years in comparison to a control catchment.

It is clear from the results above that thinning of a stand of trees should increase soil water content for at least part of the year. The amount and the period of increase will depend on the soil physical properties, the reduction in forest density and the rate of recovery in forest density.

2.5.5. Groundwater (G)

There have been very few studies outside Western Australia measuring the effect of forest density on groundwater recharge. Those reported have been in flat swampy forested areas, with groundwater systems quite different to those in the jarrah forest. All found groundwater tables to rise following selection cuts or thinning (Williams and Lipscomb 1981; Heikurainen 1967; Holstner-Jorgensen 1967). Clearfelling also leads to increases in groundwater level (Wilde *et al.* 1953, Heikurainen 1967, Holstener-Jorgensen 1967, Williams and Lipscomb 1981). Regeneration following clearfelling, or afforestation of cleared land, lowers the groundwater level (Holstener-Jorgensen 1978, Biddiscombe *et al.* 1985).

In Western Australia there have been a number of relevant studies. Carbon *et al.* (1982) found that groundwater recharge decreased with stand density for both native bushland and pine plantations on the Swan coastal plain. Sharma *et al.* (1983) found that dense pine plantations had much less groundwater recharge than the more open native banksia woodland.

In the jarrah forest there have been a number of studies. Five small forested catchments in the Collie Basin were instrumented in 1974 to quantify the effects of agricultural clearing on hydrology. Two adjacent catchments, Salmon and Wights (~ 1200 mm yr^{-1} average rainfall), were selected in the high rainfall zone. Three catchments, Lemon, Dons and Earnies (~ 800 mm yr^{-1} average rainfall) were selected in the low rainfall zone (see figure 2.3 for locations). Forest clearing treatments were carried out in 1976 on Wights catchment (totally cleared), Lemon catchment (54 per cent cleared) and Dons catchment (38 per cent cleared in a mixture of parkland clearing, strip clearing and selected soil unit clearing in different parts of the catchment). This was followed by establishment of annual agricultural plant species. Experimental details and data analyses to 1983 are described by

Williamson *et al.* (1987). Peck and Williamson (1987) found that groundwater piezometric levels on Wights catchment rose at the rate of 2.6 m yr^{-1} in the seven years following clearing in comparison to Salmon catchment which was the control. Groundwater recharge increased by half as much in Lemon catchment as in Wights, and one sixth as much in Dons catchment as in Wights.

In 1974 a paired-catchment study was established in the east of the Helena catchment to investigate the effect of selective logging on catchment hydrology. Of the two catchments, Wellbucket was logged in 1977 and Yarra was retained as a control (both ~700 mm yr^{-1} average rainfall). The logging reduced canopy density from 38 per cent to 20 per cent and basal area from 16 m^2 ha^{-1} to 11 m^2 ha^{-1} (Stokes and Batini 1985) (see figure 2.3 for location). The logging had no effect on groundwater level.

Seven small forest catchments in the southern jarrah forest were instrumented in 1976. The aim was to determine the impact of clearfelling or selective logging, followed by regeneration, on water resources in the southern forest of Western Australia. Of the seven catchments, four were treated over the period from early 1982 to early 1983 and three remained untreated as controls. March Road catchment (~1070 mm yr^{-1} average rainfall) was clearfelled and regenerated, reducing crown cover from 65 per cent to 0 per cent. April Road North catchment (~1070 mm yr^{-1} average rainfall) was clearfelled and regenerated, except for a 100 m wide stream buffer. Crown cover was reduced from 65 per cent to 0 per cent over the 90 per cent of the catchment that was treated. Lewin South catchment (~1220 mm yr^{-1} average rainfall) was heavily logged and regenerated, reducing crown cover from 70 per cent to 11 per cent and basal area from 44 m^2 ha^{-1} to 7 m^2 ha^{-1}. Yerraminnup South catchment (~850 mm yr^{-1} average rainfall) was heavily logged and regenerated except for a 50 m wide stream buffer. Crown cover reduced from 70 per cent to 10 per cent and basal areas reduced from 44 m^2 ha^{-1} to 5 m^2 ha^{-1} over the 88 per cent of the catchment that was treated. Experimental details and results to 1985 are described by Borg *et al.* (1987b) (see figure 2.3 for locations). Borewater levels rose by between 0.5 m and three m in four years following heavy cutting and regeneration. The greatest increase was in the first two years before the regeneration was well established. Taking the values for this two year period, borewater levels in Lewin South catchment rose by 1.4 m yr^{-1}, borewater levels in April Road North catchment rose by 0.7 m yr^{-1}, borewater levels in March Road catchment rose by 0.8 m yr^{-1} and borewater levels in Yerraminnup South catchment rose by 0.4 m yr^{-1}.

Another group of four small catchments in the southern forest were instrumented in 1976. All catchments were treated over the period from the end of 1976 to early 1978. There were no control catchments although there were control boreholes. The aim was to get an early indication of the effects of clearfelling or selective logging, followed by regeneration, on the water resources of the southern forest. Crowea catchment (~1380 mm yr^{-1} average raifall) was 83 per cent clearfelled and regenerated, 13 per cent selectively cut and four per cent not treated. Poole catchment (~1310 mm yr^{-1} average rainfall) was 74 per cent clearfelled and regenerated, 25 per cent selectively logged and regenerated and one per cent not treated. Iffley catchment (~1200 mm yr^{-1} average rainfall) was 83 per cent selectively cut and regenerated and 17 per cent not treated. Mooralup catchment (~880 mm yr^{-1} average rainfall) was 86 per cent selectively cut and regenerated and

14 per cent not treated (see figure 2.3 for locations). Experimental details and results are given by Borg *et al.* (1987a). Borewater levels rose by between one m and 5.5 m in the first four years following heavy cutting and regeneration, and then declined in the subsequent six years by between one m and three m. The greatest increase in borewater level was in the first two years before the regeneration was well established. Taking the values for this two year period, borewater levels in Crowea catchment rose by 1.8 m yr^{-1}, borewater levels in Poole catchment rose by 2.5 m yr^{-1}, borewater levels in Iffley catchment rose by 0.6 m yr^{-1} and borewater levels in Mooralup catchment rose by 0.3 m yr^{-1}.

In a study of factors affecting groundwater recharge on a hillslope in the northern jarrah forest, Stoneman (unpublished) found that stand basal area as well as depth to groundwater had a strong effect on the seasonal rise in borewater level.

Table 2.2 and figure 2.11 summarise the results from the literature dealing with increases in groundwater level following reductions in jarrah forest density. It is clear that reductions in

Table 2.2: Summary of results from the literature reporting increases in groundwater level following reductions in jarrah forest density

Catchment	Average rainfall ($mm\ yr^{-1}$)	Treatment	Forest Density reduction*	Post treatment monitoring	Groundwater level rise ($m\ yr^{-1}$)
Wights	1200	Agricultural development	PCF 100-0	1977-1983	2.6
Lemon	800	"	PCF 100-46	1977-1983	1.3
Dons	800	" Strip and park-land clearing	PCF 100-62	1977-1983	0.4
Wellbucket	700	Selection cut and regenerated	CD 38-20 BA 16-11	1977-1982	0
Lewin South	1220	Selection cut and regenerated	CC 70-11 BA 44-7	1982-1984+	1.4
April Road North	1070	Clearfelled except 100m buffer and regenerated	CC 65-0	1982-1986+	0.7
March Road	1070	Clearfelled and regenerated	CC 65-0	1982-1986+	0.8
Yerraminnup South	850	Selection cut except 50m stream buffer and regenerated	CC 70-10 BA 44-5 over 88% of area	1982-1984+	0.4
Crowea	1380	3.5% not treated 83.3% clearfelled 13.2% selectively cut & regenerated	BA 44-3	1977-1979+	1.8
Poole	1310	0.8% not treated 74.4% clearfelled 24.8% selectively logged and regenerated	BA 44-3	1977-1979+	2.5
Iffley	1200	16.6% not treated 83.4% selectively cut & regenerated	BA 44-16	1977-1979+	0.6
Mooralup	880	14.3% not treated 85.7% selectively cut & regenerated	BA 44-16	1977-1979+	0.3

* PCF = Per cent of catchment forested
CD = Crown density
BA = Basal area
CC = Canopy cover

\+ These years were selected because they represent the peak response in groundwater level before the effect of regeneration

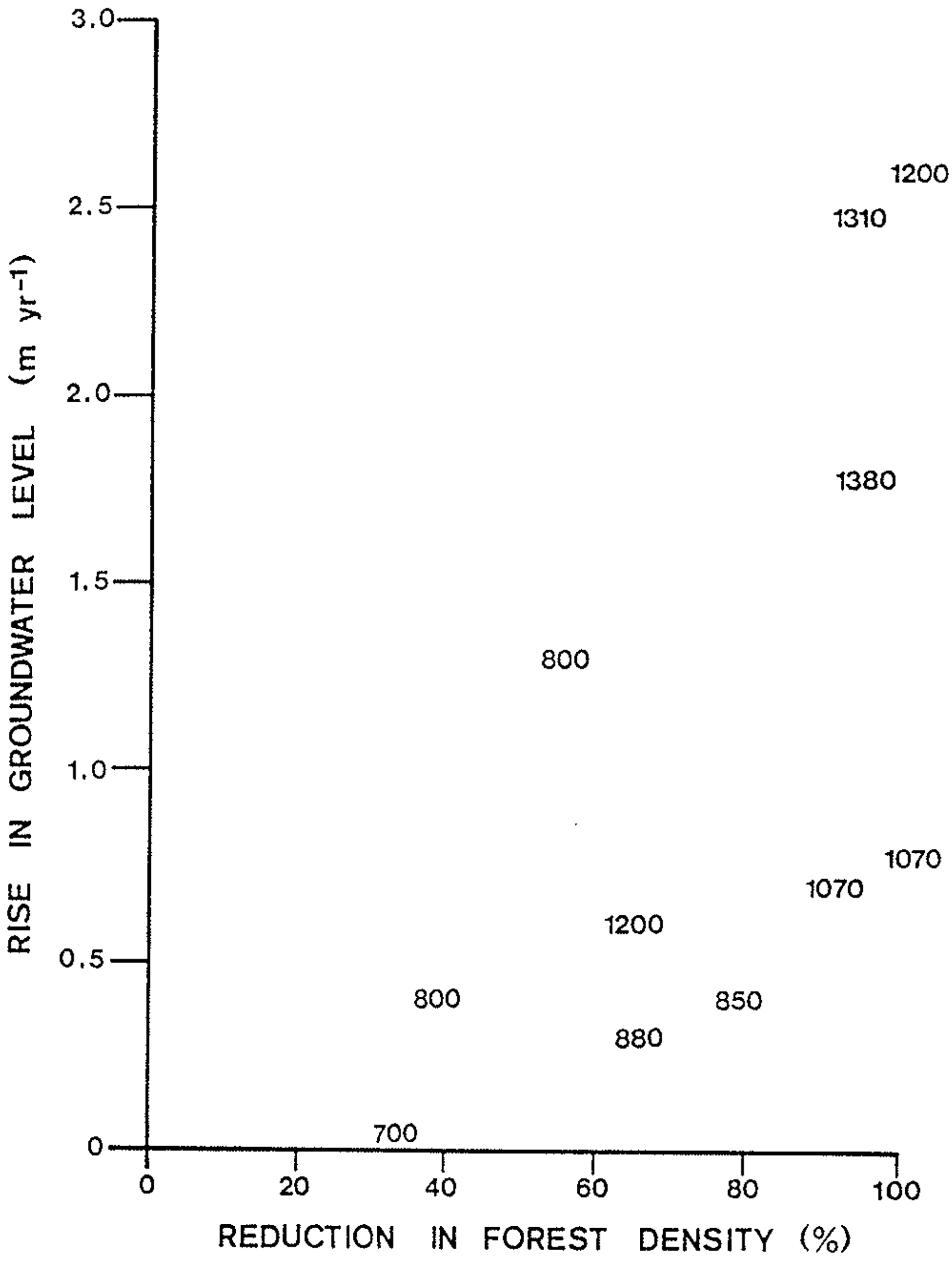

Figure 2.11: Relationship between rise in groundwater level and the reduction in forest density. Note: numbers indicate the average annual rainfall (mm).

forest density will lead to increases in groundwater recharge and rises in groundwater level. Other things being equal, the greater the reduction in forest density then the greater the increase in groundwater level. In the jarrah forest the other major factor influencing the increase in groundwater level is rainfall. Other things being equal, the greater the annual rainfall then the greater the increase in groundwater level.

2.5.6. Streamflow (W)

2.5.6.1. *Agricultural clearing of jarrah forest catchments*

Wights catchment (~1200 mm yr^{-1} average rainfall) was totally cleared and the effect on its hydrology was dramatic (Williamson *et al.* 1987). Streamflow, expressed as a percentage of rainfall, has increased for the seven years following clearing, and may still be increasing. In the first two years following clearing streamflow increased by 120 mm or 13 per cent of rainfall. A conservative estimate of the long term increase in streamflow is the average of the 1981-83 increases. Values of 27.1 per cent of rainfall, or the equivalent of 325 mm are obtained for a 1200 mm

yr^{-1} rainfall area. This represents an increase in streamflow of over 300 per cent in comparison to that expected had the catchment not been cleared.

Lemon catchment (~800 mm yr^{-1} average rainfall) was 54 per cent cleared. To 1983 only a small increase in streamflow had occurred (Williamson *et al.* 1987). This was approximately 2.1 per cent of rainfall, or 17 mm in a 800 mm yr^{-1} rainfall area. However, groundwater levels are rising rapidly and there should be significant increases in streamflow when it reaches the ground surface. This is estimated to occur by 1990 (Hookey 1987).

Dons catchment (~800 mm yr^{-1} average rainfall) was 38 per cent cleared. Again there was a small increase in streamflow (Williamson *et al.* 1987). This averaged 1.4 per cent of rainfall or 11 mm in a 800 mm yr^{-1} area. As with Lemon catchment, groundwater levels are rising in cleared areas. It will be some years before the full impact on streamflow is observed. It is clear from the above results that the total impact of forest density reduction on streamflow is delayed in lower rainfall areas.

2.5.6.2. *Clearfelling and logging of jarrah forest catchments*

On all the treated catchments in the southern forest described by Borg *et al.* (1987b), highest streamflow increases, expressed as percentage of rainfall, occurred within two years of treatment. The subsequent reduction in streamflow increase in the third year after treatment probably signifies the impact of forest regeneration. However, there are too few post-treatment years for this to be substantiated.

Streamflow increases averaged for 1983/84 from the high rainfall zone Lewin South catchment (~1220 mm yr^{-1} average rainfall) were 11.8 per cent of rainfall, or 144 mm.

Streamflow increases for March Road catchment (~1070 mm yr^{-1} average rainfall) and April Road North catchment (~1070 mm yr^{-1} average rainfall) are slightly greater than that of Lewin South catchment, despite lower rainfalls. This is attributed to these catchments being clearfelled. The 1983/84 average increases for these catchments are: March Road 15.2 per cent of rainfall or 163 mm, April Road North 13.8 per cent of rainfall or

148 mm. The slightly smaller streamflow increase of April Road North relative to March Road catchment may be due to the retention of a stream buffer on April Road North. Yerraminnup South catchment (~850 mm yr^{-1} average rainfall) in the low rainfall zone produced somewhat smaller streamflow increases in response to heavy logging. The 1983/84 average increases were 4 per cent of rainfall or 34 mm.

Wellbucket catchment (~700 mm yr^{-1} average rainfall) was selectively cut. The increase in streamflow was negligible over the five years following treatment (Stokes and Batini 1985).

2.5.6.3. *Comparison of jarrah forest results with results from the literature*

Most studies have found an immediate increase in streamflow following clearfelling and regeneration treatments. Streamflow typically reaches a maximum in the first or second year, and then declines back to prelogging levels. The rate of decline is dependent on the rate of regeneration of the vegetation. However, in the mountain ash (*Eucalyptus regnans*) forests of Victoria the water usage of the regrowth regenerated following bushfire was so great that very substantial reductions in streamflow below pre-fire levels resulted (Langford 1976, Kuczera 1985). Reductions in streamflow after the replacement of old-growth forest with regrowth have also been reported in the northern jarrah forest (Schofield *et al.* 1988), and are considered likely in the karri (*Eucalyptus diversicolor*) forest of Western Australia (Borg and Stoneman in press).

There have been a great many studies of the effects of forest treatments on streamflow. These have been reviewed by Hibbert (1967) and Bosch and Hewlett (1982). They concluded that reductions in vegetation density lead to increases in streamflow. Bosch and Hewlett (1982) reported that for each 10 per cent reduction in cover there was an average increase in streamflow of 40 mm for pine and eucalypt forest types. Results from studies of the effect of clearing, clearfelling and regenerating, and logging of jarrah forest catchments are reviewed above in sections 2.5.5.1 and 2.5.5.2.. The responses of streamflow to reductions in forest density are substantially less for the jarrah forest than for the general trends reported by Bosch and Hewlett (1982) particularly in the early years following treatments (figures 2.12 and 2.13).

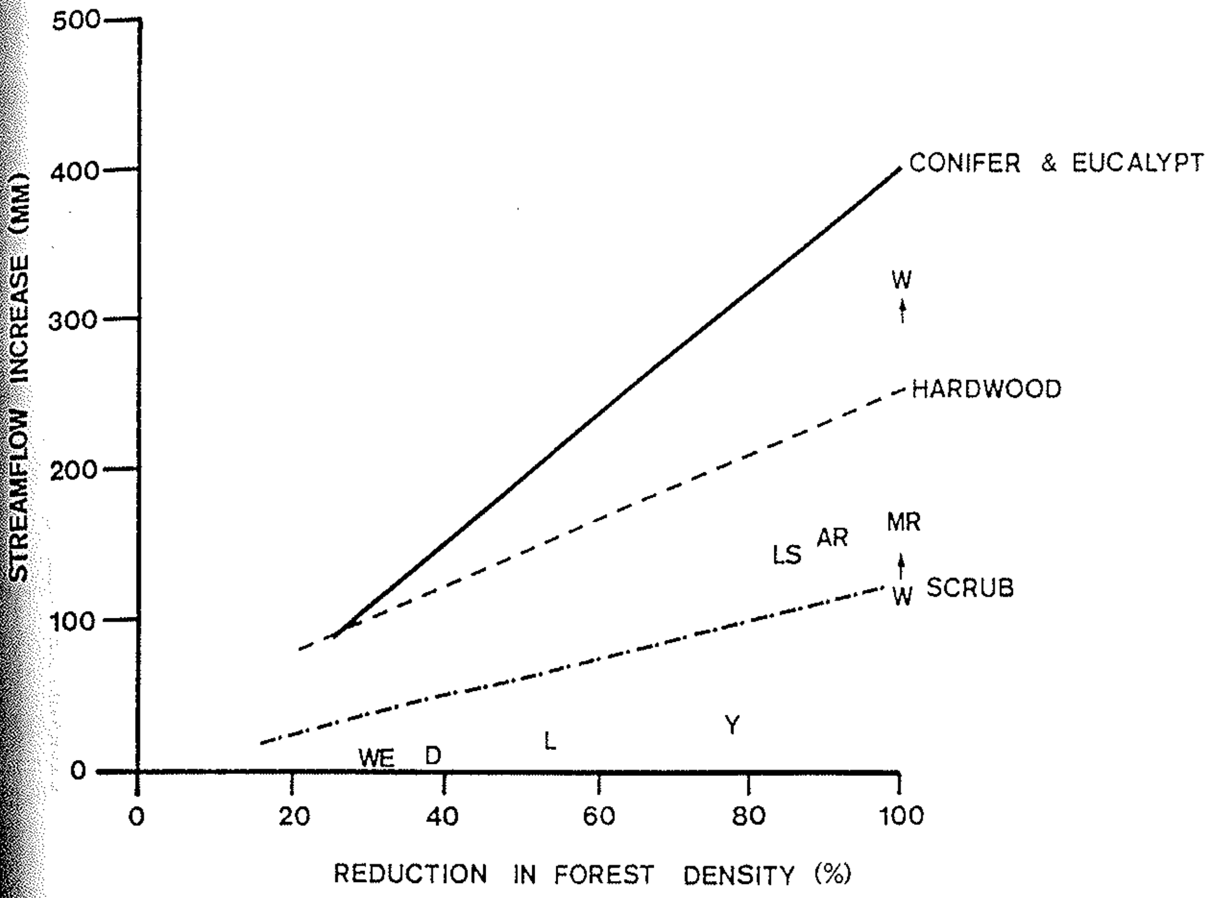

Figure 2.12: Comparison of streamflow increases due to reductions in forest density for jarrah forest catchments with those reported by Bosch and Hewlett (1982). Symbols for jarrah forest catchments are: AR = April Road North, D = Dons, L = Lemon, LS = Lewin South, MR = March Road, W = Wights, WE = Wellbucket, Y = Yerraminnup South. Arrows show change in streamflow increase for Wights from first two years after clearing to the fifth to seventh years after clearing.

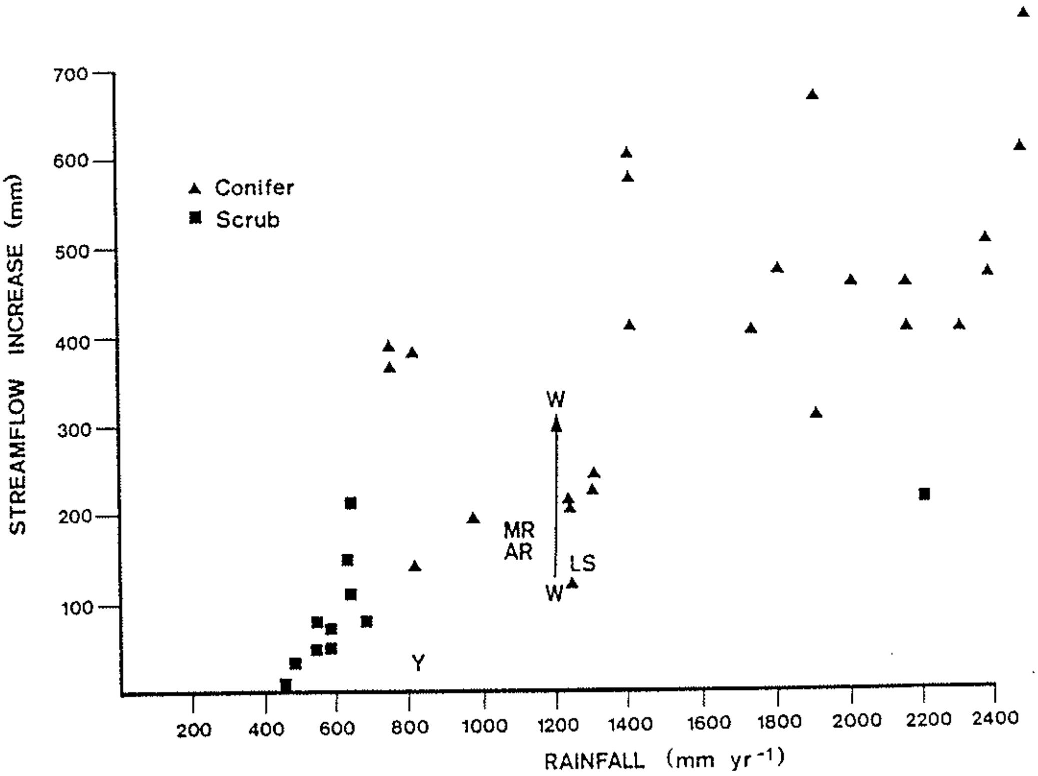

Figure 2.13: Comparison of streamflow increases following clearcutting (or close for some jarrah forest catchments) of conifer, scrub and jarrah, as a function of average annual rainfall. Conifer and scrub data from Bosch and Hewlett (1982). Symbols for jarrah forest catchments are: AR = April Road North, LS = Lewin South, MR = March Road, W = Wights, Y = Yerraminnup South.

The reasons for this smaller response of streamflow to reductions in forest density of jarrah forest compared to other forest may be attributable to significant differences in both climate and soils. The mediterranean climate with a long summer drought means that transpiration is often limited by the availability of soil water. In dense stands where the rate of transpiration is greater, soil water will limit transpiration earlier than in less dense stands, but in the end the same amount of water may be transpired. This may also occur to a smaller extent in winter in the intervals between rainfall events. Thus the reduction in forest density of jarrah forest may not result in as great an increase in streamflow as a similar reduction in forest density in climates where transpiration is not as greatly limited by soil water availability.

The deep soils of the jarrah forest may also play an important part. These soils have the capacity to store large amounts of water, and thus to store a large amount of the reduction in evapotranspiration. In catchments which are cleared and not regenerated this will result in a time lag in the streamflow response. This is illustrated in figure 2.12 by the lag in streamflow response of Wights catchment; in the first two years after clearing streamflow only increased by 120 mm, but by five to seven years after clearing the streamflow increase was 325 mm. However, where catchments are regenerated or increase in forest density following treatment a large part of the increase in soil water storage may be transpired by the vegetation before it is reflected in an increase in streamflow. Therefore, treatments which cause only short term reductions in forest density will not see the reduction in evapotranspiration reflected in a similar increase in streamflow because the regenerating vegetation will have the opportunity to transpire this soil water. However, treatments which cause longer term reductions in forest density e.g. thinning of jarrah stands, should eventually see a large part of these increases in soil water reflected in increases in streamflow.

Both of these effects i.e. climate and soil, are more extreme in lower rainfall catchments. This is due firstly to the greater excess of potential evaporation over rainfall which means that less dense vegetation has a greater capacity than in higher rainfall catchments to transpire an equivalent amount of water as dense vegetation. Secondly, the lower ratio of rainfall to soil water storage capacity means that there will be a longer time lag before increases in soil water storage are reflected in increases in streamflow. This also gives the vegetation a longer period to increase in density and to transpire the stores of soil water before they are lost to streamflow. Thus the lower rainfall jarrah forest catchments show some of the smallest increases in streamflow in the world to reductions in forest density (figure 2.12).

Chapter 3: Experimental Hypotheses

3.1. Effect of Thinning on Tree and Stand Growth of Jarrah

It is well established from the literature that thinning can lead to an increase in tree growth rate. This has also been shown for jarrah, though not for uneven-aged stands, and not for large trees.

There is ample evidence in the literature to show that stand growth can be maintained following thinning of an even-aged stand. However, there are little data dealing with thinning of uneven-aged stands. The little information that exists indicates that thinning of uneven-aged stands is likely to maintain or increase stand increment.

There is much literature dealing with the effects of thinning on merchantable volume growth. However, no simple relationship between the two is obvious. There are a many factors which influence the effect of thinning on merchantable growth. These include (i) the `time period' between the thinning and the remeasurement, (ii) the `growth rate' of the trees, (iii) the `size class distribution' of the unthinned and thinned stands, (iv) the `intensity of thinning', and (v) the `proportion of degraded trees' in the stands and how effectively thinning removes these degraded trees (see section 2.3). By keeping these factors in mind it should be possible to test the effect of thinning on merchantable growth in specific circumstances.

This experiment tests the hypothesis that thinning of the uneven-aged forest on the Yarragil 4L catchment will (i) increase the growth of jarrah trees, (ii) increase stand growth of jarrah, and (iii) increase merchantable volume growth of jarrah by transferring growth onto trees with a better utilization status.

3.2. Effect of Thinning on Streamflow and Groundwater

Reductions in forest density have been shown in many catchment experiments around the world to lead to increases in streamflow (Bosch and Hewlett 1982). In hydrological systems which are dominated by groundwater flows rather than by streamflow, reductions in forest density have been shown to lead to increases in groundwater recharge and groundwater levels (Butcher 1977).

The jarrah forest is an unusual hydrological system in having both a significant streamflow system and a significant groundwater system. The interaction between these two systems may be particularly important in determining the hydrologic effects of a reduction in forest density (Reuprech and Schofield 1989).

Clearing for agriculture of jarrah forest catchments leads to sustained increases in streamflow and groundwater recharge. However, clearing arrests wood production. Thinning, on the other hand, has the potential to maintain or increase wood production while increasing streamflow and groundwater levels.

This experiment tests the hypothesis that thinning of an uneven-aged catchment will increase streamflow and raise groundwater levels.

Chapter 4: Materials and Methods

4.1. Outline of Experimental Design

A first order catchment of 125 ha, the Yarragil 4L catchment, was selected to be thinned and streamflow was measured from 1976 for this catchment and a group of control catchments. The control catchments were other first and second order catchments in the Yarragil catchment which is a fourth order catchment. Groundwater levels were measured monthly at a valley and a midslope location in the Yarragil 4L catchment and a group of control catchments. This approach allows regression equations to be established from the pretreatment data and used to predict changes in streamflow and groundwater level following thinning.

The diameter, height and utilization status of jarrah trees in various size classes and site-types in the thinned catchment and surrounding unthinned control stands were measured in 1985. This approach allows a comparison of the growth of trees between thinned and unthinned stands.

4.2. Yarragil Catchment

The Yarragil catchment has an area of 7070 ha. It is located about 15 km south east of Dwellingup and is mainly in the intermediate rainfall zone of the northern jarrah forest (figures 4.1, 1.1 and 2.3). The catchment comprises a range of geomorphological and vegetational types typical of this zone (see Appendix A).

The Yarragil catchment is fully forested except for roads. The forest has been subject to fuel reduction burning on about a seven year cycle. Jarrah dieback (caused by *Phytophthora cinnamomi* Rands) is evident mainly in the valley bottoms. Some of these areas have been cleared and replanted with eastern Australian eucalypts.

The soils and landforms vary with increasing dissection from east to west. The broad valley systems in the east and centre of the catchment have truncated lateritic profiles (Yarragil landform). The steep sided valleys in the west have shallower soils formed over more recently exposed basement granite and dolerite (Murray

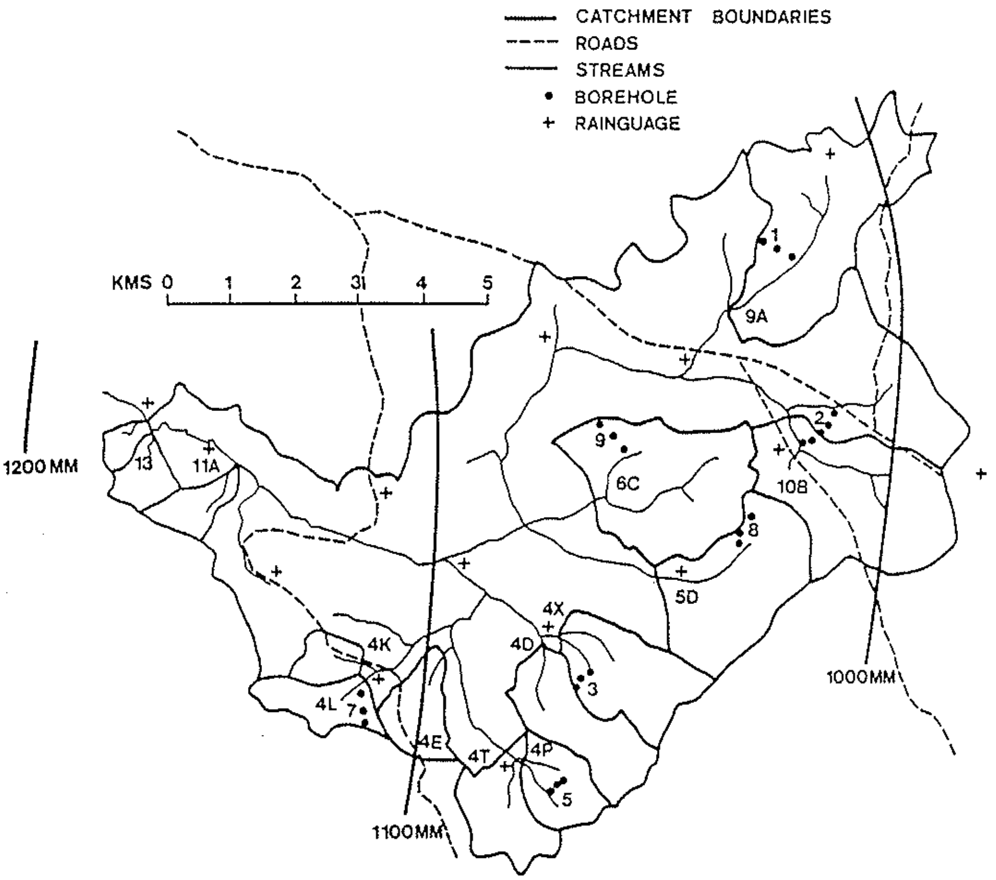

Figure 4.1: Yarragil catchment showing catchments monitored, borehole transects, rainfall isohyets and rainguages.

landform). The uplands have fully developed lateritic profiles which are greater than 30 metres in depth (Dwellingup landform) (McArthur *et al.* 1977; Herbert *et al.* 1978).

The Yarragil catchment is comprised of numerous subcatchments, 13 of which have been intensively studied. The Yarragil 4L catchment is one of these 13. The other 12 catchments are used in this thesis to assess the representativeness of the 4L catchment (Appendix A) and for determining the response of streamflow and groundwater to thinning.

4.3. Yarragil 4L Catchment

The Yarragil 4L catchment is a relatively small catchment of 125 ha. It is located high in the local landscape, and has relatively subdued topography and little incision of the streambed (Figures 4.2 and 4.3). The forest is uneven-aged and composed of the P, PW, T, TP and WC site-vegetation types (Havel 1975). Average annual rainfall is 1120 mm. Average annual streamflow prior to thinning was 4.3 mm. From the three boreholes in the catchment groundwater salinity is about 200 mg L^{-1} T.D.S.. Salt storage is low at

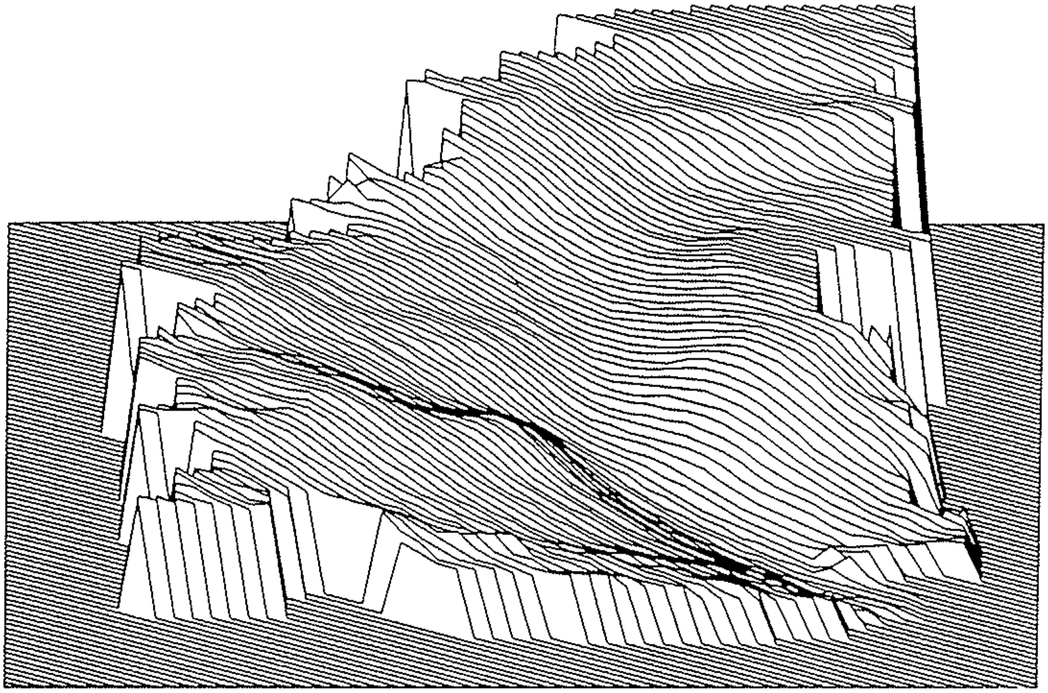

Figure 4.2: Three dimensional map of the Yarragil 4L catchment.

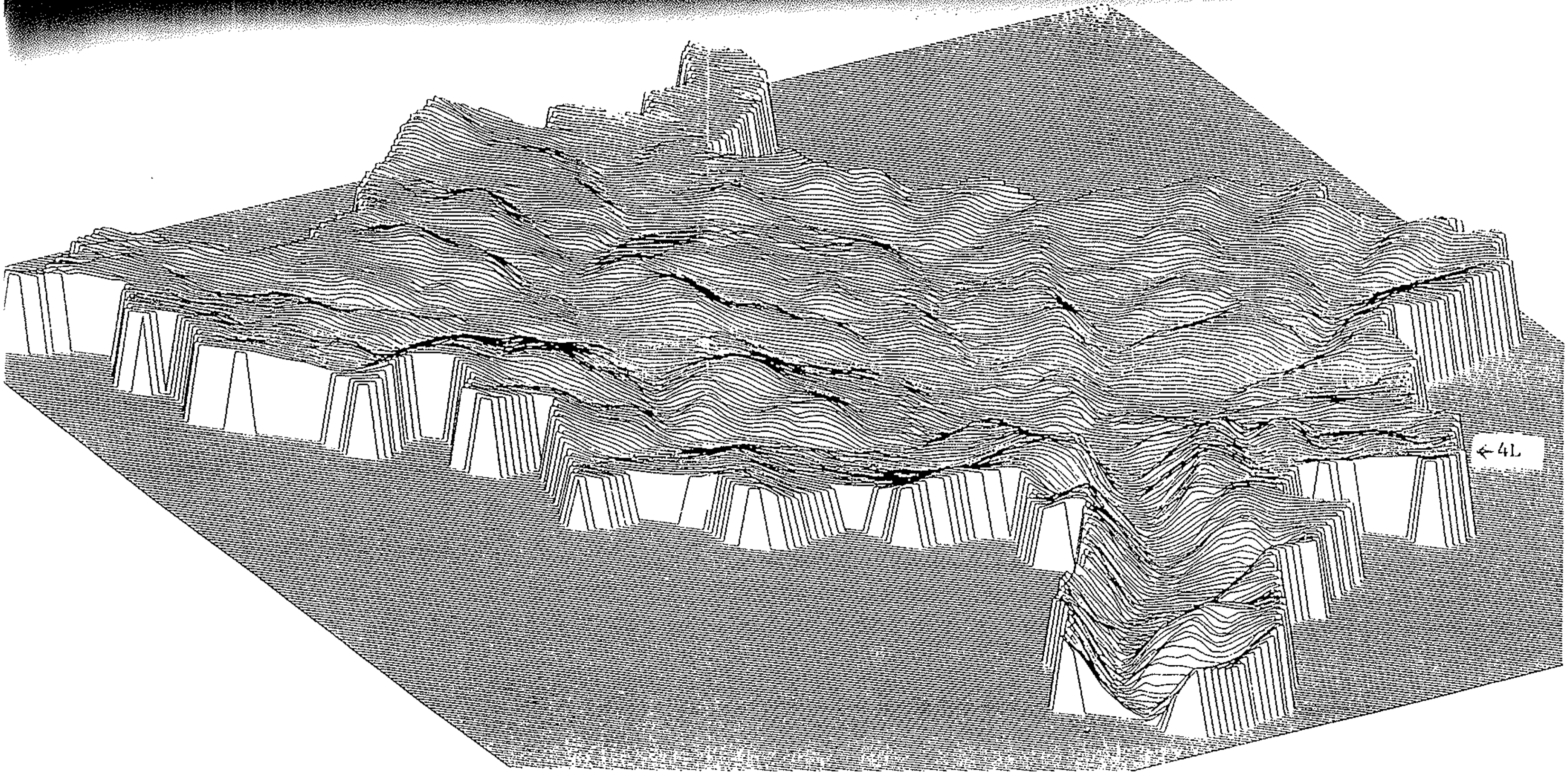

Figure 4.3: Three dimensional map of the Yarragil catchment, with 4L on the right hand edge.

6.5 kg m^{-2} T.D.S. (Ritson *et al.* 1981). A detailed description of the vegetation and morphologic characteristics of 4L and the control catchments is in Appendix A.

4.4. Logging History and Forest Structure

The forest on the Yarragil catchment can be considered uneven-aged, with the regrowth having regenerated from cutting mainly between 1920 and 1945. The silvicultural practise during this period varied from group selection cutting to a relatively light uniform selection cut (Stoneman *et al.* 1988a). The application of these broad silvicultural practices was variable and probably depended on a number of factors including stand structure and composition prior to logging, levels of timber damage, merchantability standards and markets, proximity to the mill, availability of labour and finance, preferences of the treemarker and the level of supervision of the logging operation. Stand structure and age composition of stands resulting from this cutting was therefore highly variable and any catchment is composed of virtually the full range of tree sizes and ages.

4.5. Thinning of the Catchment

Treemarking of the catchment was undertaken in January and February 1983 with the objective of selecting and marking crop trees for retention so that a canopy cover of 20 per cent would be retained. The specifications for crop trees and the spacing to be retained is described in Appendix C. The catchment was commercially logged for general purpose sawlogs in February and March 1983. Following this all other trees not marked for retention were cull fallen in a non-commercial thinning operation which was completed by mid May 1983. A fire to remove logging slash was completed over about two-thirds of the catchment in late winter 1983 and over the remainder in winter of 1984. A tops disposal operation to remove debris from around the base of crop trees was done over the summer of 1983/84. The catchment received a fuel reduction burn in the spring of 1984. This fire resulted in crown scorch over about 10 per cent of the catchment. There was virtually 100 per cent crown scorch in the swamp and valley portion. Stump and ground coppice was poisoned over the summer of 1984/85 by foliar spraying with Roundup herbicide at a concentration of 1 part Roundup in 10 parts water.

4.6. Forest Density Measures

Canopy cover was estimated using an instrument similar to the one described by Montana and Ezcurra (1980). Basal area and stocking were estimated from sampling lines established 200 metres apart and running north-south across the catchment. All species were included in these measures of canopy cover, basal area and stocking. Trees > 15 cm diameter at breast height over bark but < 30 cm diameter at breast height over bark which were within five m on the right hand side of the centre line were measured. Trees > 30 cm diameter at breast height over bark within ten metres of the centre line were measured. The diameter at breast height over bark measurements were also used to estimate leaf area index using the regression equation of Carbon *et al.* (1979). Sapwood area (at 1.3 m above ground) was calculated using the equation

$$SA = 5.969\ dbhub - 43.4$$

where SA is sapwood area (cm^2) and dbhub is diameter at breast height under bark (cm) (Whitford pers. comm.). The statistics for the equation are

$r^2 = 0.85 \quad n = 27 \quad p < 0.0001$

The regression equations used to predict both leaf area index and sapwood area should only be considered to give a general indication of the leaf area index and sapwood area before and immediately after thinning.

The effect of the thinning on forest density is presented in table 4.1. The thinning led to about a two-thirds reduction in forest density.

4.7. Stand Structure

It is argued that the younger and more vigorous trees have been retained in the thinning for the following reasons. Firstly, there is a difference in the distribution of size classes of the jarrah trees in the thinned stand compared with the control stand (table 4.2). The thinned stand has a greater proportion of its jarrah trees in the smaller size classes compared to the unthinned stand, particularly in the range from 25 cm to 55 cm diameter at breast height over bark. This means that there will be a difference in age distributions of the stands with the thinned stand being on average slightly younger than the control stand. Secondly, the more vigorous and faster growing trees have been selected for retention (see

Table 4.1

Forest density in the Yarragil 4L catchment before and after thinning

	Before Thinning	After Thinning	Reduction (%)
Canopy Cover (%)	55	22	60
Basal Area (m^2 ha^{-1})	35	11	69
Stocking (spha > 15cm dhb)	275	100	64
Leaf Area Index	1.9	0.6	68
Sapwood Area (m^2)	3.92	1.35	66

Table 4.2: Per cent of jarrah trees for the thinned and unthinned stands in each size class

Size Class Midpoint DBHOB (cm)	Unthinned (UT)	Thinned (T)	(T/UT)
10	1.0	0.3	0.33
20	16.3	17.0	1.04
30	24.6	26.0	1.06
40	20.8	24.4	1.17
50	12.6	14.8	1.17
60	8.6	8.2	0.95
70	6.7	4.9	0.73
80	5.1	1.7	0.33
90	1.0	1.3	1.30
100	0.8	0.3	0.38
110	1.2	0.6	0.5
120	0.6	0.6	1.0
130	0.4	0.0	-
140	0.0	0.0	-

Appendix C). This is done on the basis of their crown dimensions (Stoneman *et al.* 1988a). Within a given size class the fastest growing trees are those with the deeper and wider crowns, and these are the trees selected for retention. Faster growing trees of a given size must be younger than equal sized trees which are slower growing. It follows then that within each size class the younger and more vigorous trees are the ones that are retained.

4.8. Experimental Procedure Dealing With Tree and Stand Growth of Jarrah

The tree and stand growth analysis is only on the jarrah component of the stand. Jarrah trees comprised 60 per cent of stand basal area prior to thinning and 73 per cent of stand basal area after thinning.

4.8.1. Location of measurement strips

(i) Thinned: North-south lines 200 m apart in the 4L catchment were used as the centre lines of assessment strips. A 10 per cent sample of jarrah trees > 30 cm diameter at breast height over bark was taken by assessing jarrah trees within 10 m of either side of the line. A 2.5 per cent sample of jarrah trees > 15 cm diameter at breast height over bark but < 30 cm diameter at breast height over bark was taken by assessing 5 m on the right hand side of the line.

(ii) Unthinned: Control lines were located outside the catchment boundary to pair up with each of the site-types within 4L. The lines were of a sufficient length to give a similar sample size to that from 4L. As in 4L, jarrah trees > 30 cm diameter at breast height over bark within 10 m either side of the line were measured. Jarrah trees > 15 cm diameter at breast height over bark but < 30 cm diameter at breast height over bark within five m on the right hand side of the line, were measured. Figure 4.4 shows location of measurement strips inside and outside 4L.

4.8.2. Utilization assessment

Jarrah trees were assessed during 1983 for conversion to the following products:

Currently saleable products

a) general purpose sawlogs, and

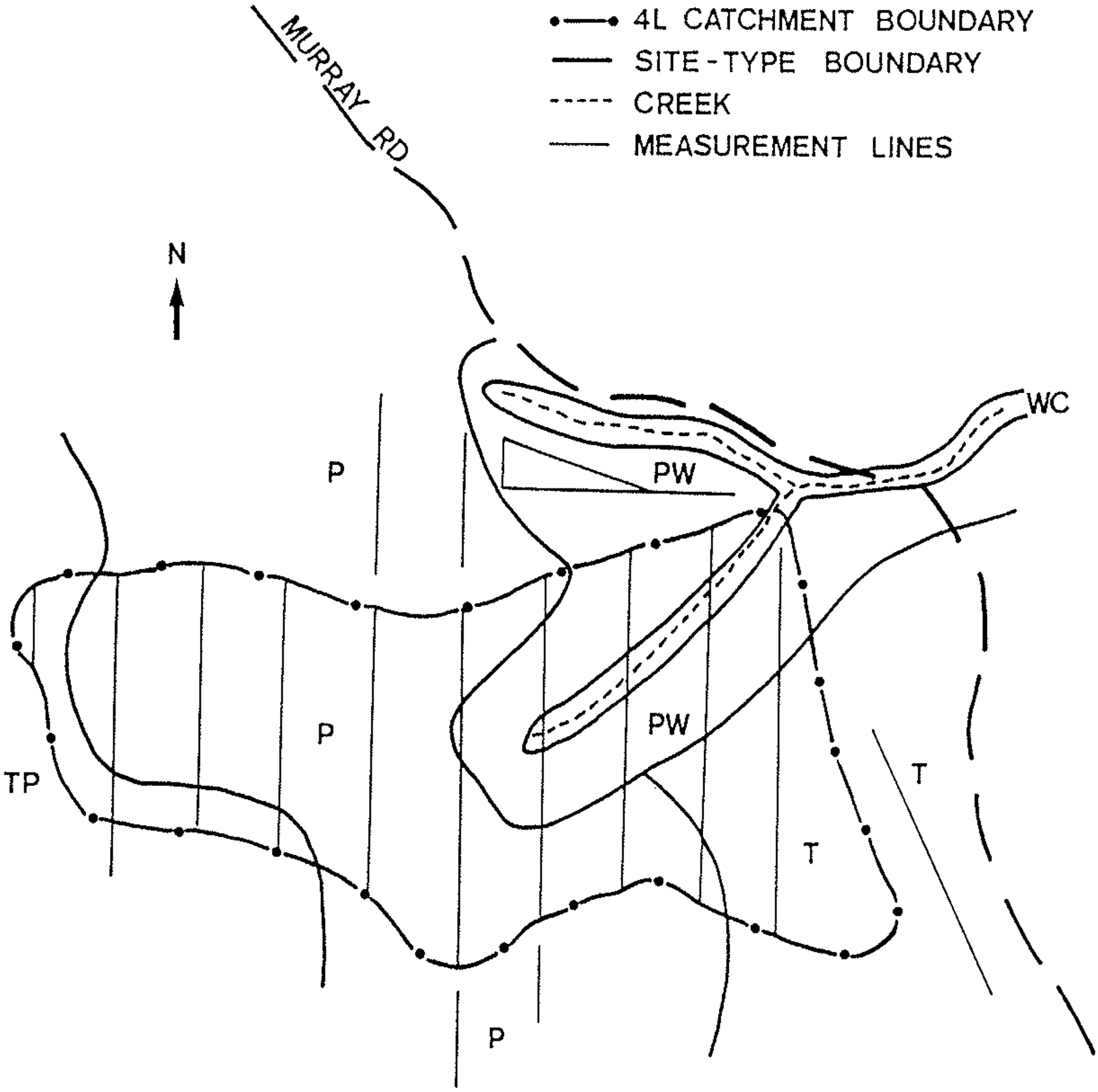

Figure 4.4: Location of measurement strips and site-types inside and outside the Yarragil 4L catchment.

b) poles.

Potentially usable products

a) veneer logs,

b) salvage sawlogs,

c) chipwood, and

d) minor forest produce.

Not usable.

General purpose sawlogs were assessed at current (1983) acceptability standards using the method outlined by Batini and Williamson (1971). The specifications for the various wood products are listed in table 4.3. All other sections between stump height and crown break which had not been assessed as in one of the above classes were recorded as not usable.

4.8.3. Tree growth measurements

The diameter at breast height over bark of each jarrah tree was measured in January 1985 and again in January 1986. Trees with defects at the height of measurement were noted.

Table 4.3: Specifications for wood products assessed in the study area.

SPECIFICATION	CURRENTLY SALEABLE		POTENTIALLY SALEABLE					
						MINOR FOREST PRODUCE		
						FIREWOOD		
	GENERAL PURPOSE SAWLOGS	POLES	VENEER	SALVAGE SAWLOGS	CHIPWOOD	LOGWOOD	CORDWOOD	FENCEPOSTS
MIN. LENGTH	2.1m	9.5m	2.6m	2.1m	3.4m	1m	1m	2m
MIN. DBHOB	50cm	25cm	30cm	35cm		30cm	15cm	30cm
MIN. TOP DOB	25cm	15cm	20cm	25cm	25cm			
STRAIGHTNESS		Reasonably straight from crown to 1.5m of base.	<30mm deflection in any 2.6m. Two straight opposite sides required.		<150mm deflection in any 3.4m.	Reasonably straight.	Must be straight.	Reasonably straight.
ALLOWABLE DEFECTS	>50% solid wood. No borers.	No limbs within 2m of top. ≤1 limb in each 2m length, and <⅓ diameter of crown. Pin holes and dry sides acceptable.	No visual faults. Spiral grain <⅓ diameter in any 2.6m.	>35% solid wood. May be top logs in trees with no bottom log.	Burnt bark but not burnt wood. Rot to be <15%. No forks. Must be able to be debarked.	Some charcoal acceptable. No hollow buts.		

4.8.4. Tree growth analysis

Only those jarrah trees which had no sign of defect at the height of measurement were included in the analysis in order to avoid atypical growth measurements. The mean diameter over bark growth and standard errors were calculated.

4.8.5. Stand basal area over bark growth analysis of jarrah

Jarrah stand basal area over bark growth was calculated by multiplying the tree mean basal area over bark growth for the defect-free trees by the total number of jarrah trees (including those with defects at height of measurement) for each size class in each site-type in each thinning treatment. This total jarrah stand basal area over bark growth was divided by the area sampled for each size class in each site-type in each thinning treatment to give a jarrah stand basal area over bark growth in m^2 ha^{-1}.

4.8.6. Stand volume increment analysis of jarrah

It was assumed that trees had not grown from one utilization class into another in the short period between measurements. The jarrah stand volume increment was extrapolated up to include trees with defect at the height of measurement in the same way as was done for jarrah stand basal area over bark growth.

4.9. Tree Growth Efficiency

The growth efficiency of a tree is the annual growth of bole wood per unit of leaf area (Waring and Schlesinger 1985). Growth efficiency was calculated for a range of size classes of trees in both the thinned and unthinned stands by dividing the mean basal area over bark growth for the size class by the leaf area corresponding to the midpoint of the size class. The leaf area was calculated using the equation of Carbon *et al.* (1979). The increase in growth efficiency due to thinning was then calculated for each size class by subtracting the growth efficiency of the unthinned trees from the growth efficiency of the corresponding thinned trees.

4.10. Experimental Procedure Dealing With Streamflow and Groundwater

4.10.1. Rainfall

Rainfall was measured weekly in storage rainguages. Rainguages were located in various locations in the catchment (see figure 4.1). The Thessien polygon method was used to determine catchment rainfall.

4.10.2. Streamflow measurements

Thirteen catchments have been instrumented since 1976 with combination V-notch weirs and Stevens F type recorders to measure and record the height of water flowing over the weir. This record is then digitized and daily, monthly and yearly streamflows computed.

4.10.3. Analysis of streamflow response

Regression equations were established for yearly streamflow between the 4L catchment and the 12 Yarragil control catchments for the pretreatment period (table 4.4). These regressions were used to predict the streamflow for 4L and an average was

Table 4.4: Regressions equations for streamflow from the Yarragil 4L catchment compared with other Yarragil catchments.

Intercept	Slope	Catchment	Years	r^2
-3.72	0.55022	4D	1976-1982	0.90
-1.06	0.14967	4E	"	0.76
-0.86	0.31949	4K	"	0.98
-0.84	0.15899	4P	"	0.75
-0.65	0.19312	4T	"	0.79
-0.68	0.44135	4X	"	0.81
-0.63	0.69458	5D	"	0.77
0.30	0.64837	6C	"	0.77
0.61	0.91535	9A	"	0.76
0.37	0.00571	11A*	"	0.89
-6.64	0.60083	13	"	0.94
-1.46	0.56219	10B	1980-1982	0.99

* regression equation for this catchment was of the form $y = bx^2 + a$

taken and compared to the observed flow. The number of regression equations which were used to derive the streamflow response of 4L varied from year to year. They were as follows: 1976 to 1979 - 11, 1980 to 1982 - 12, 1983 - 11, 1984 - 10, 1985 - 10. The reasons for the varied number of regression equations was (i) the 10B wier was not built until 1980, (ii) a track was built just upstream of the 4D weir in 1983 which changed its streamflow pattern and therefore the regression based on this weir was not used further, and (iii) the 4P weir developed a leak in 1985 therefore the regression based on this weir was not used further.

4.10.4. Groundwater measurements

Twenty-seven boreholes were drilled in locations selected over the whole of the Yarragil catchment to sample the main geomorphological features (figure 4.1). On completion of drilling, each borehole was fitted with a piezometer made from 42 mm internal diameter poly-vinyl chloride tubing. The lower end of each piezometer had longitudinal slits spiralling the tubing for a length determined by the position and anticipated fluctuation of the groundwater table. Where there was no groundwater table, only the bottom 6 m of tubing had slits. Boreholes were backfilled with coarse sand (0.001-0.002 m diameter) to at least one metre above the top of the split section. A slurry of sand and cement was added to seal this lower section before backfilling the remainder with drilling spoil. A 0.7 m section of the tube protruded above the soil surface and was protected with an earthenware pipe set in concrete (Herbert *et al.* 1978). In the bores that contained enough water for sampling, groundwater level was monitored monthly from May 1975.

4.10.5. Analysis of groundwater response

Regression equations were established for each month of the year between boreholes with reasonable pretreatment regression fits i.e. $p < 0.05$. The midslope borehole in the 4L catchment was regressed against other boreholes in similar landscape positions. The valley borehole in the 4L catchment was regressed against other valley boreholes. Coefficients of determination range between 0.52 and 0.94 for the valley boreholes and 0.74 and 0.99 for the midslope boreholes.

Chapter 5: Effect of Thinning on Tree and Stand Growth of Jarrah

5.1. Results

5.1.1. Growth of jarrah trees

Diameter over bark growth was much greater for the thinned trees than for the unthinned trees (0.64 cm ± 0.02 cm compared with 0.16 cm ± 0.02 cm) (table 5.1). Similarly, diameter over bark growth was much greater in each size class for the thinned trees compared with the unthinned trees. The thinned trees on each site grew significantly more than the unthinned trees on the same sites.

Thinned trees in each size class on each site-type also grew more compared with the unthinned trees (table 5.1).

The effect of thinning is evident over all size classes when the diameter over bark growth for the thinned and unthinned trees is graphed for a much greater number of size classes (figure 5.1). The greatest and most reliable response is between 20 cm and 60 cm diameter at breast height over bark. For the unthinned trees, the larger trees

Table 5.1: Diameter over bark growth (cm yr^{-1}) for jarrah trees in thinned (T) and unthinned (UT) stands. Note: any two means that are followed by the same letter are not significantly different.

SITE-TYPE		T		TP		P		PW		TOTAL	
TREATMENT		T	UT	T	UT	T	UT	T	UT	T	UT
SIZE CLASS											
15-29.9	x	0.65	0.21	0.48	0.20	0.45	0.12	0.61	0.17	0.53	0.17
	s.e.	0.11	0.06	0.03	0.08	0.06	0.05	0.11	0.04	0.05	0.03
	n	19	30	4	9	60	48	29	35	112	122
lsd group										b	a
30-44.9	x	0.86	0.29	0.74	0.17	0.70	0.11	0.58	0.07	0.70	0.16
	s.e.	0.09	0.06	0.13	0.09	0.04	0.06	0.06	0.04	0.03	0.03
	n	34	44	15	12	109	41	55	44	213	141
lsd group										c	a
45+	x	0.71	0.15	0.46	0.23	0.67	0.16	0.54	0.18	0.64	0.16
	s.e.	0.13	0.06	0.31	0.19	0.06	0.05	0.12	0.06	0.05	0.03
	n	20	33	5	3	94	55	30	29	150	120
lsd group										bc	a
Total	x	0.77	0.22	0.64	0.19	0.64	0.13	0.58	0.13	0.64	0.16
	s.e.	0.06	0.03	0.12	0.06	0.03	0.03	0.05	0.03	0.02	0.02
	n	73	107	24	24	263	144	114	108	475	383
lsd group		c	a	bc	a	bc	a	bc	a	bc	a

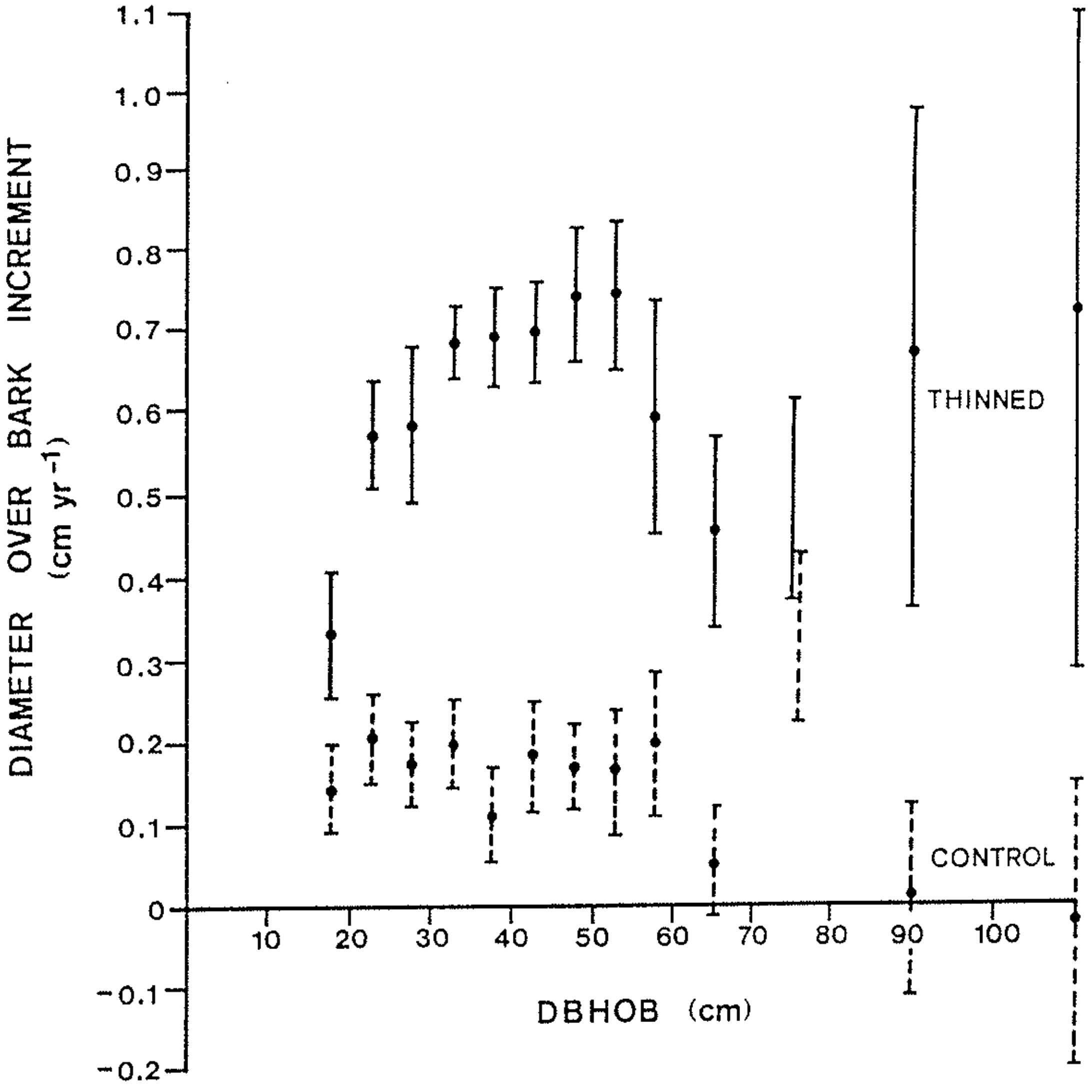

Figure 5.1: Response of diameter increment to thinning for a range of tree size classes in the Yarragil 4L catchment. Dots and bars indicate means and standard errors respectively.

grew less and had a greater variability in growth rate. For the thinned trees the 15-20 cm size class grew less than most other size classes and the larger trees had a much greater variability in growth rate than the smaller trees.

For the unthinned trees, diameter over bark growth was not significantly different among size classes or among sites (table 5.1). However, for the thinned trees the 15-30 cm size class grew significantly less than the 30-45 cm size class (table 5.1).

5.1.2. Stand basal area over bark growth of jarrah

Stand basal area over bark growth of jarrah (m^2 ha^{-1}) was 2.49 times greater in the thinned area than the unthinned area. Stand growth of jarrah was greater for the thinned area than the unthinned area for each size class. Stand growth of jarrah was greater for the thinned area than the unthinned for each site-type except for the TP site-type which had a low sample size. Thinned areas in each size class in each of the T, P and PW site-types had a greater stand basal area over bark growth of jarrah than in the corresponding unthinned areas (table 5.2).

5.1.3. Stand volume growth of jarrah

Stand volume growth of jarrah was 1.94 times greater in the thinned area than in the unthinned area. Stand volume growth of jarrah was more for the thinned area than the unthinned area for each size class and for the T, P and PW site-types, but not the TP site-type. Stand volume growth of jarrah in each size class of each site-type was greater for the thinned areas than the unthinned area except for the 15-30 cm size class of the T and TP site-types (table 5.3).

5.1.4. Per cent volume increment of jarrah in each utilization class

The ratio of thinned to unthinned total volume increment is 1.94. However, the ratio of thinned to unthinned general purpose sawlogs + veneer logs volume increment is 3.43 (table 5.4). The per cent volume increment shows that more of the growth of the thinned stand is going into the higher value veneer and general purpose sawlog products and a

TABLE 5.2: Stand basal area over bark increment (baobi) of jarrah (m^2 ha^{-1}) for the thinned (T) and unthinned (UT) stands.

SITE	T		TP		P		PW		TOTAL	
TREATMENT	T	UT	T	UT	T	UT	T	UT	T	UT
SIZE CLASS										
15-29.9										
BAOBI/HA	.1250	.0856	.0452	.1227	.0890	.0406	.1139	.0115	.0972	.0450
n(defect free) *	19	30	4	9	60	48	29	35	112	122
n(defective) *	5	3	1	2	20	6	8	4	34	15
30-44.9										
BAOBI/HA	.1154	.0710	.0798	.0460	.0977	.0135	.0915	.0120	.0977	.0263
n(defect free) *	34	44	15	12	109	41	55	44	213	141
n(defective) *	9	5	2	1	45	11	21	8	77	25
45+										
BAOBI/HA	.0893	.0574	.0650	.0367	.1241	.0485	.0868	.0467	.1053	.0491
n(defect free) *	20	33	5	3	94	55	30	29	150	120
n(defective) *	7	14	6	3	38	25	18	16	69	58
TOTAL										
BAOBI/HA	.3297	.2140	.1900	.2054	.3108	.1026	.2922	.0702	.3002	.1204
n(defect free) *	73	107	24	24	263	144	114	108	475	383
n(defective) *	21	22	9	6	103	42	47	28	180	98

* Defective and defect free trees were those respectively with and without sign of defect at the height of measurement.

Table 5.3: Stand volume increment of jarrah (m^3 ha^{-1}) for the thinned and unthinned stands.

SITE TYPE	T		TP		P		PW		TOTAL	
TREATMENT	T	UT	T	UT	T	UT	T	UT	T	UT
SIZE CLASS										
15-29.9	0.69	0.70	0.22	0.80	0.54	0.26	0.79	0.41	0.60	0.42
30-44.9	0.76	0.50	0.38	0.16	0.60	0.10	0.51	0.07	0.59	0.19
45+	0.60	0.41	0.53	0.20	0.99	0.40	0.56	0.34	0.71	0.37
TOTAL	2.06	1.66	1.13	1.16	1.97	0.76	1.85	0.84	1.90	0.98

Table 5.4: Volume increment (m^3 ha^{-1}) and per cent volume increment for jarrah in the thinned (T) and unthinned (UT) stands for a range of wood products.

	T		UT	
	(m^3 ha^{-1})	(%)	(m^3 ha^{-1})	(%)
Veneer	0.13	6.9	0.01	1.0
General purpose sawlogs	0.35	18.5	0.13	13.3
Salvage sawlogs	0.05	2.6	0.03	3.1
Pole	0.04	2.1	0.02	2.0
Chipwood	0.37	19.6	0.05	5.1
Minor forest produce	0.88	46.6	0.61	62.2
Not usable	0.10	5.3	0.11	11.2
Total	1.90	100	0.98	100

lower proportion is going into the lower value minor forest produce and not usable products. Therefore, thinning has concentrated growth onto trees with a better utilization status.

5.1.5. Tree growth efficiency

Tree growth efficiency increased in all size classes in response to thinning (figure 5.2). The largest increases in growth efficiency were in the smaller size classes with a peak response in the 35-40 cm diameter at breast height over bark size class. The increase in growth efficiency in response to thinning then decreased as size class increased.

5.2. Discussion

5.2.1. Tree growth of jarrah

Individual tree growth rates responded to thinning, which conforms to previous results from the literature. The response is similar to other thinning experiments in even-aged jarrah stands (Stoneman *et al.* 1988 a).

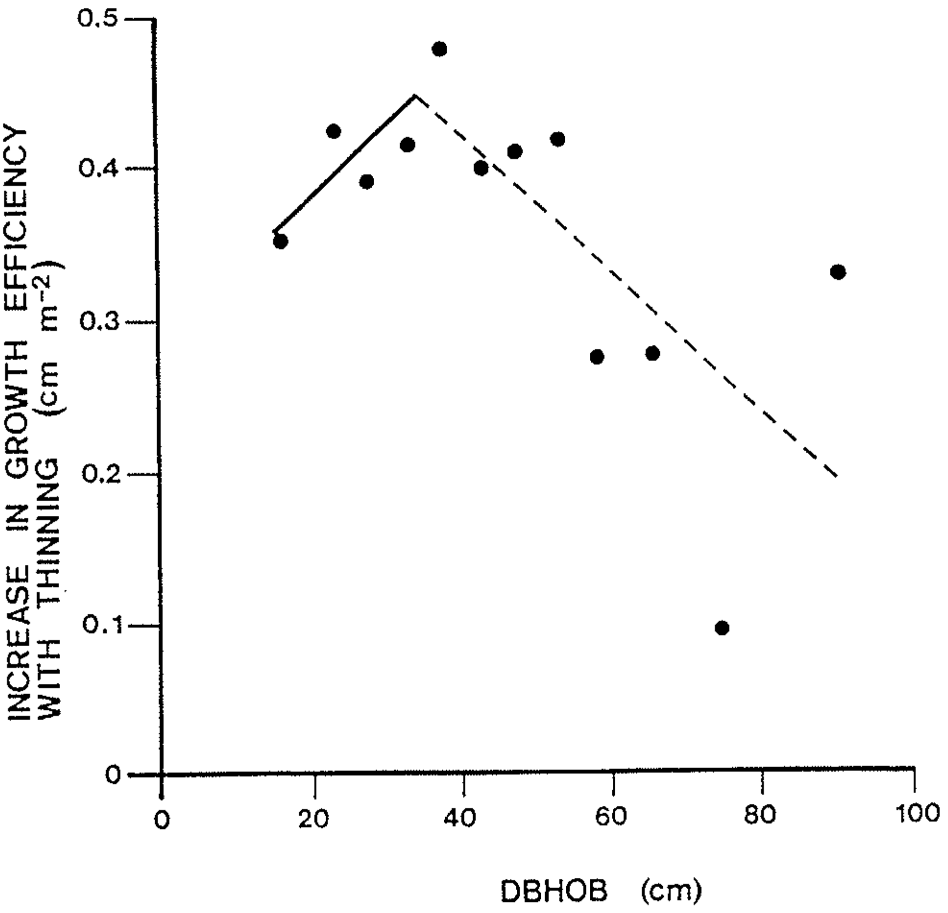

Figure 5.2: Increase in tree growth efficiency in response to thinning for a range of tree size classes in the Yarragil 4L catchment.

The larger trees in this experiment did generally respond to thinning. This response is surprising because it is often considered that these large trees are not suffering competition from the smaller trees around them and that their aged physiological system may not have the capacity to respond to thinning. However, there was much greater variability in their response than in the response of smaller trees. This is probably because of the variability in crown vigour of the individual trees. Pole sized trees have much less variability in crown vigour (Stoneman unpublished data) and have much less variability in their response to thinning.

5.2.2. Stand growth of jarrah

Stand growth of jarrah also increased with thinning, which is not consistent with the results from the literature for even-aged stands (see Section 2.12). The increase is also surprising since there is generally a positive linear relationship between stand growth and leaf area index (Linder 1984), and leaf area index was reduced by two-thirds in this experiment (table 4.1).

The increase in stand growth of jarrah is attributed to an increase in growth efficiency, which in turn is due to the reduction in competition. Waring *et al.* (1981) showed for an even-aged Douglas fir (*Pseudotsuga menziesii*) stand that trees in lightly stocked stands had higher growth efficiencies than those in heavily stocked stands. Stoneman (1987) has also shown this to be the case for an even-aged jarrah stand following thinning. In the case of Stoneman (1987) the increase in growth efficiency was only enough to compensate for the reduction in leaf area index and stand growth was virtually the same over the range of stand densities studied.

For the uneven-aged stands of this catchment the increase in growth efficiency was so great that an increase in stand growth resulted. This is because the relatively young and vigorous trees were retained (see Section 4.6) and have responded particularly well to the reduction in competition. This is reflected in figure 5.2 where the increase in growth efficiency due to thinning is greatest in the smaller size classes.

These increase in growth efficiency more than compensate for the reduction in leaf area index and in turn lead to an increase in stand growth of jarrah.

There are other possible explanations for this increase in stand growth of jarrah with thinning. Firstly, there may be a change in partitioning of assimilates. Less may be allocated below ground and much more of the assimilates are able to go to above ground growth. This could result because there is less water stress following thinning. Secondly, perhaps it is merely a short term response to mobilisation of additional nutrients from the large quantity of woody debris and burnt remains of woody debris. This nutrient influx would tend to change the partitioning of assimilates from below ground to above ground. Thirdly, the increase in stand growth of jarrah may be because of an increase in the jarrah component of the stand. However, the jarrah component has only increased from 60 per cent of basal area before thinning, to 73 per cent of basal area after thinning (Stoneman 1986a). This is not a large enough increase to account for the doubling in stand growth. The growth response may be because of a short-term butt swell following thinning and possibly this is a typical short-term response for jarrah (including even-aged stands). No short term responses for jarrah have been previously reported. Another possible explanation is that it is a product of poor experimental design. Measurements both before and after thinning for both control and thinned areas would give conclusive results. However, this is an unlikely explanation because of the consistency across all size classes and site-types in the results (tables 5.1 - 5.3).

5.2.3. Merchantable growth

Thinning has clearly concentrated growth onto trees with a better utilization status. There is over three times as much growth going into high quality products (veneer and general purpose sawlogs) in the thinned area compared with the unthinned area.

As time passes this effect will become even greater. Trees in the thinned area will progress more rapidly than those in the unthinned area into higher value wood products.

Less than half the growth of the thinned stand is accrued into minor forest produce compared with over 60 per cent in the unthinned stand. The minor forest produce in the thinned stand is of much better quality than in the unthinned stand. In the thinned stand only the well-formed individuals of the smaller trees were retained. Most of these are classified as minor forest produce, but will grow into general purpose sawlogs. In the unthinned stand most of the minor forest produce is of poor form. Much is also likely to die before reaching sawlog size.

Chapter 6: Effect of Thinning on Streamflow and Groundwater

Earlier results were reported and discussed by Stoneman (1986b).

6.1. Results

6.1.1. Rainfall

The average annual rainfall and the long term average annual rainfall for each of the 13 study catchments show rainfall for the study period was 15 per cent less than average (table 6.1). Whilst years of below average rainfall are not unusual, a sequence of years such as occurred in the study period is unusual, and has not been observed previously. The 10 year moving average for Dwellingup from 1934 to 1986 is now at it's lowest level in the record (figure 6.1).

6.1.2. Streamflow

In the first year after thinning there was not a significant increase in streamflow (figure 6.2). In the second year after thinning there was a slight increase in streamflow of 3.0 mm ± 1.1 mm

Table 6.1: Long term average annual rainfall and annual rainfall for the study period for Yarragil 4L and control catchments.

Catchment	Average Annual Rainfall 1976-1985 (mm)	Long Term Average Annual Rainfall (mm)
4L	932	1120
13	983	1160
11A	956	1150
4K	933	1120
4E	930	1100
4T	938	1080
4P	938	1080
4D	942	1080
4X	918	1070
5D	888	1040
6C	878	1060
9A	866	1030
10B	834	1020
Mean	918	1085

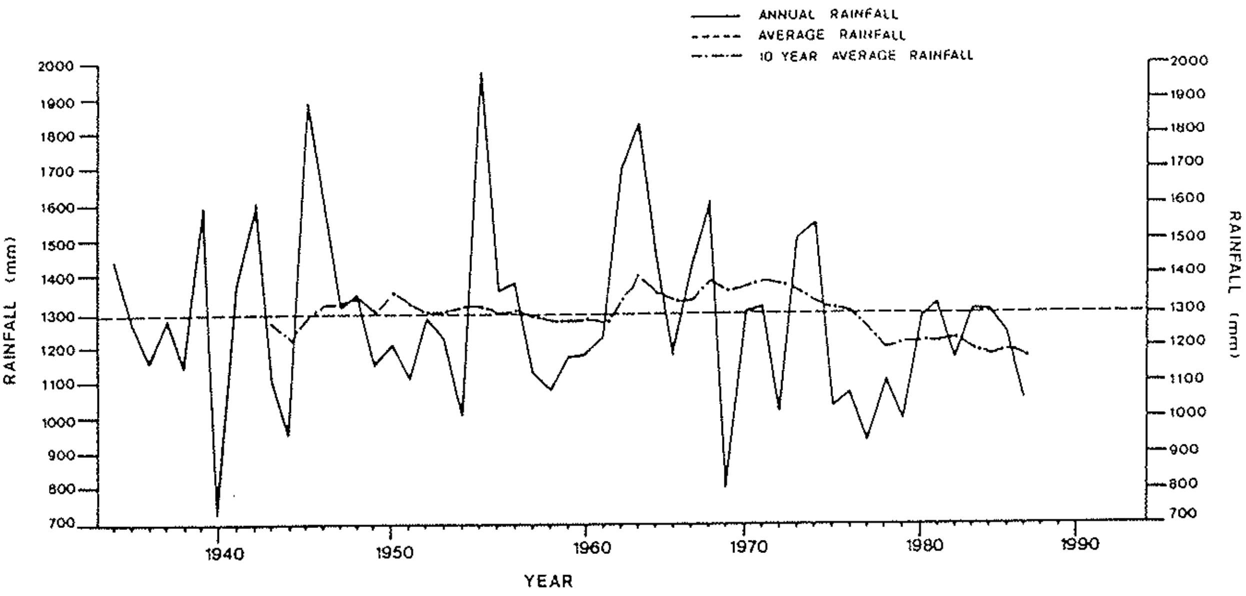

Figure 6.1: Annual rainfall and 10 year moving average rainfall for Dwellingup.

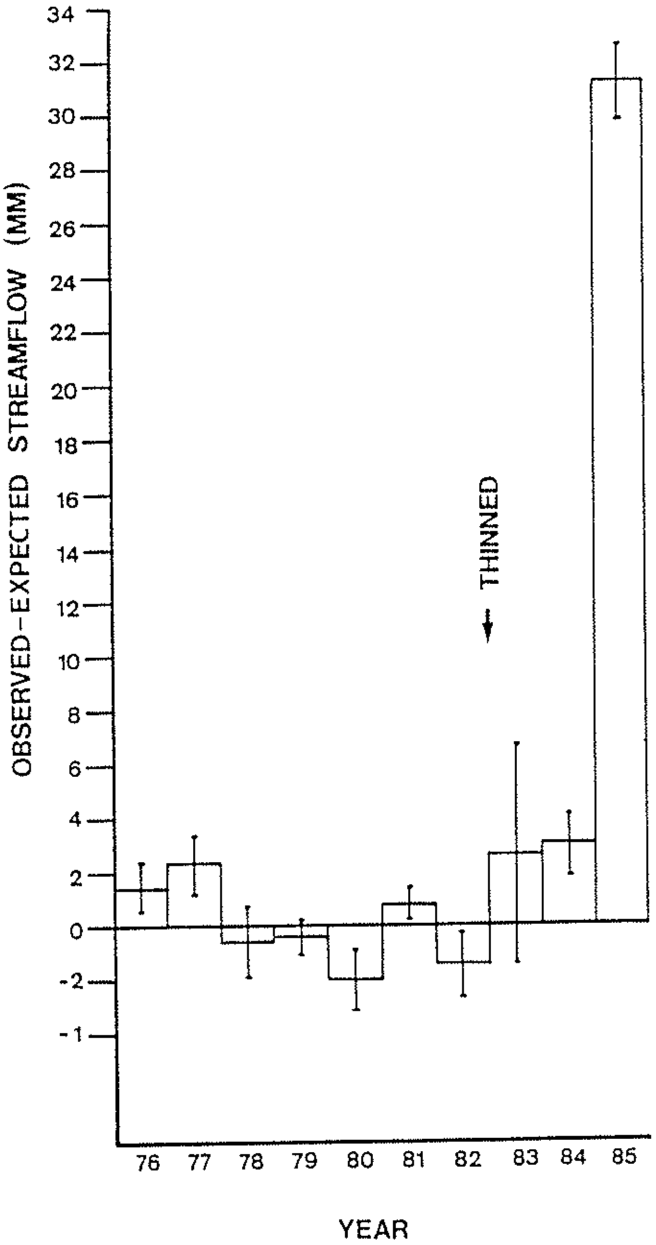

Figure 6.2: Increase in Yarragil 4L streamflow following thinning. Bars indicate standard errors.

which is equal to an increase of 58 per cent over the predicted streamflow. In the third year there was an increase of 31.9 mm ± 2.0 mm which is equal to an increase of 541 per cent over the predicted streamflow.

6.1.3. Groundwater

The groundwater level in the midslope borehole in 4L dropped from a level of 18 m below the surface in 1976 to 23 m in 1983. The level then rose following thinning (figure 6.3). In the pretreatment period the control boreholes had similar depths to groundwater and showed similar patterns in level. The declining groundwater level is because of below average rainfall. The groundwater level in the midslope borehole in 4L showed a steady rise of one m yr^{-1} relative to control bores in the four years following the thinning (figure 6.3). After four years, groundwater level in this borehole had risen four metres in comparison to control boreholes.

The groundwater level in the valley borehole in 4L ranged seasonally between two m and seven m in depth in the pretreatment period (figure 6.4).

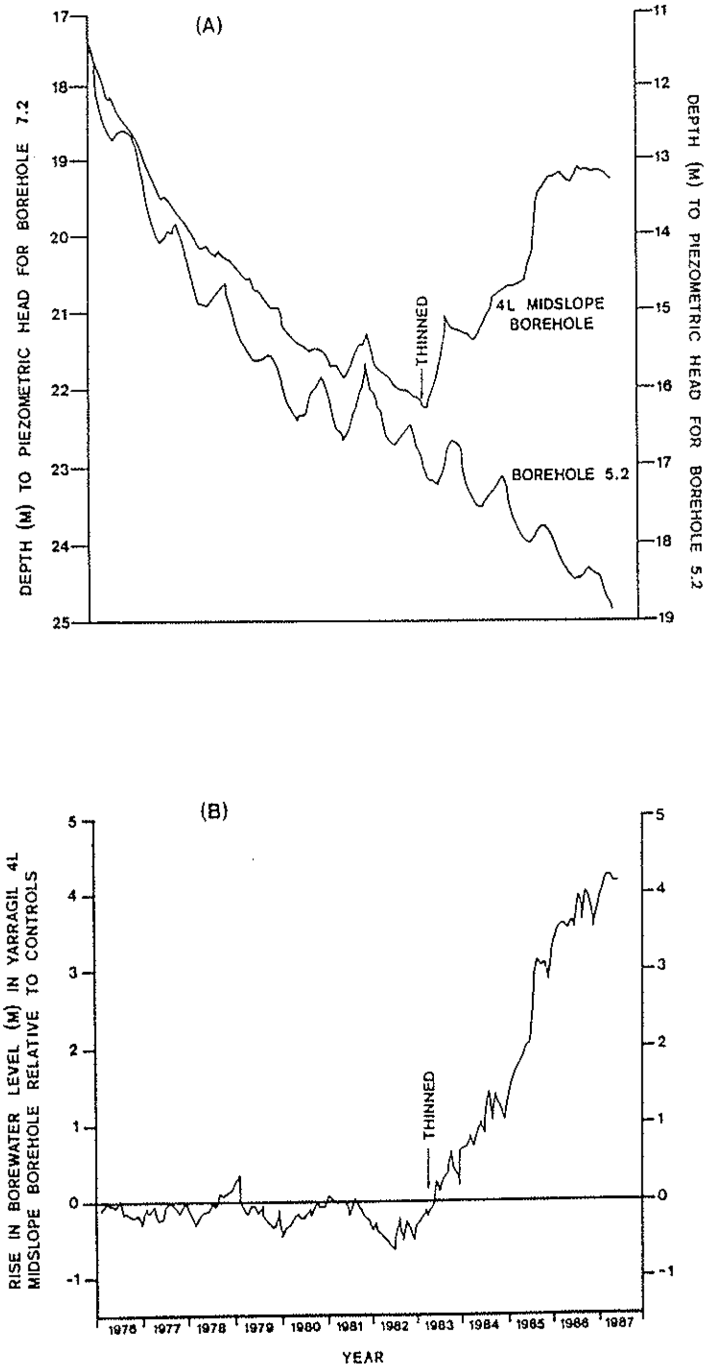

Figure 6.3: Increase in groundwater level in the Yarragil 4L midslope borehole following thinning.

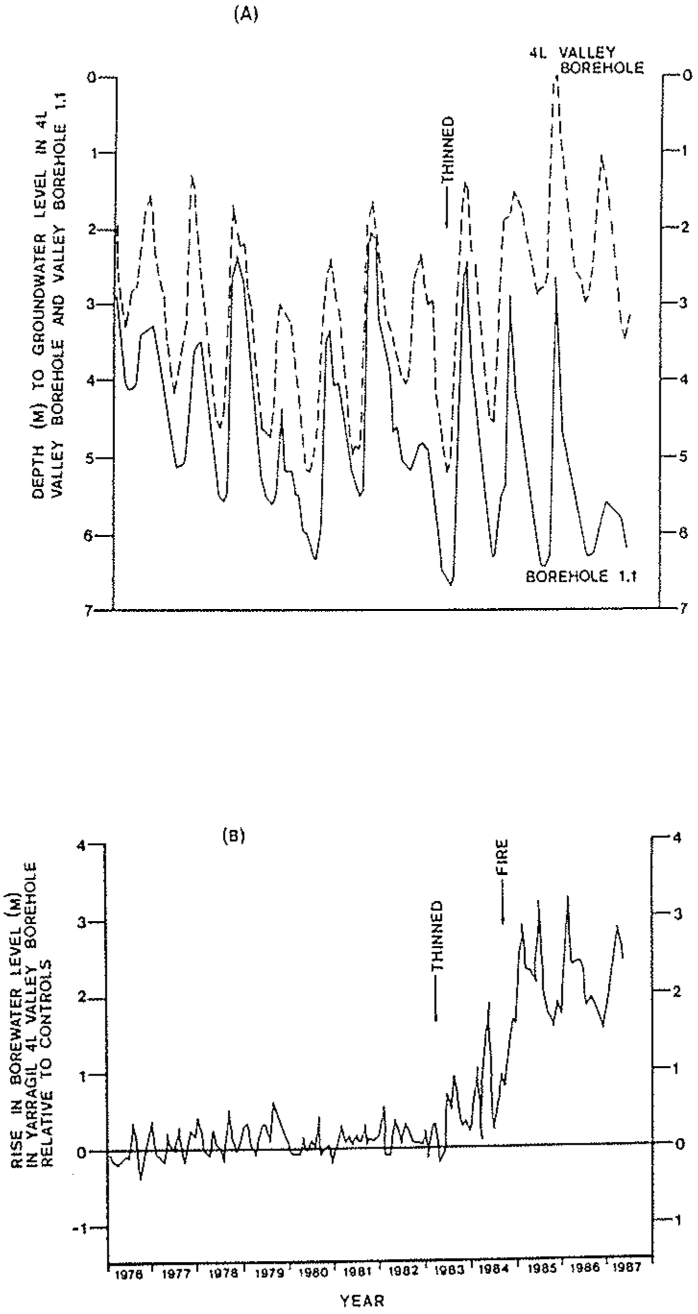

Figure 6.4: Increase in groundwater level in the Yarragil 4L valley borehole following thinning.

During this period the groundwater level in the control boreholes showed similar depths to groundwater and similar seasonal fluctuations in level. The pattern of response of groundwater level in the valley borehole was different to that in the midslope borehole. There was little increase in level in the first year, but a large response in the second year after the thinning (figure 6.4). Most of this response was following a spring fire in the catchment which burnt off most of the swamp vegetation in the valley. After two years, groundwater level in the valley borehole had risen more than two metres in comparison to control boreholes. In the third and fourth years after the thinning groundwater levels in the valley borehole did not rise significantly more.

6.2. Discussion

Rainfall for the study period was well below average in comparison to the whole period of record. Therefore, care must be taken in interpreting and extrapolating the results. Higher rainfall typically generates more surface and shallow subsurface flow and hence more streamflow. There is also more groundwater recharge, which leads to higher groundwater levels, and more streamflow source areas. The effects triggered by higher rainfall on the relationships between streamflow and groundwater levels, and their interaction for different catchments are complex. The effect will depend on such factors as catchment shape, topography, soils and landscape position.

Whilst there were large per cent increases in streamflow in the first three years relative to those that would have been expected had the catchment not been thinned, the increases in absolute terms are small. This contrasts the results of other catchment experiments reported in the literature (Bosch and Hewlett, 1982). Moreover, all of these experiments have reported the largest increase in streamflow in the first couple of years following treatment. Streamflow later diminishes as the forest regrows and leaf area builds up. This could suggest that the prospect of increasing streamflow by thinning jarrah forest catchments is poor.

However, the depth and large soil water storage capacity of jarrah forest soil make the response different from those reported in the literature. The capacity of jarrah forest soils to absorb reductions in evapotranspiration is illustrated by the clearing of Wights catchment. Sharma et al. (1982) found that in the first year following the clearing of Wights, soil water storage in the top six m increased by 220 mm in comparison to the still forested Salmon catchment. Williamson et al. (1987) have also shown that streamflow from Wights took many years to reach a new equilibrium. There was a considerable lag between clearing of the catchment and the peak response in streamflow. Wights is also an extreme catchment in terms of incision in the catchment. The 4L catchment has much more subdued topography. This, combined with the less extreme treatment of the catchment, means the response of streamflow will be much slower than in Wights.

Additionally, the slow recovery in leaf area index of jarrah pole stands following thinning and subsequent coppice control (figure 2.8) means that the recovery in water use by vegetation will also be slow. Therefore, the peak response in streamflow following thinning may occur many years after the thinning and a streamflow response is likely to persist for many years beyond this peak response. The much greater increase in streamflow in the third year following thinning (31.9 mm ± 2.0 mm) supports the argument that there will be a considerable lag between thinning and the peak response in streamflow. In summary, the prospects of increasing streamflow by thinning of jarrah forest catchments is not accurately indicated in the early years following the thinning.

The increase in streamflow is substantially less than those of southern jarrah forest catchments following heavy logging and regeneration (see section 2.5.5). Borg *et al.* (1987a b) reported streamflow increases in excess of 100 mm yr^{-1} for high and intermediate rainfall zone catchments, and 40 mm yr^{-1} for the low rainfall zone Yerraminnup South catchment. The 4L increase is less than expected from high and intermediate rainfall zone catchments and is also less than the Yerraminnup South response. These differences in the size of streamflow increase in the first few years following treatment can be largely attributed to 4L being an extreme upland catchment with very gentle slopes (see Chapter 4 and Appendix A) and a large soil water and groundwater storage capacity. Yarragil 4L has great depths to groundwater and large unsaturated and saturated water stores to fill before an excess of rainfall over evapotranspiration becomes apparent as streamflow.

Groundwater response, in contrast to streamflow response, has been quite dramatic. Groundwater rises for the midslope borehole of about one m yr^{-1} support the contention that there have also been large increases in unsaturated soil water storage such as those reported for the clearing of Wights catchment (Sharma *et al.* 1982). In Wights catchment groundwater levels rose at the rate of 2.6 m yr^{-1} (Peck and Williamson 1987). By accepting Bestow's (1976) estimate of the storage coefficient of similar material (0.039), and neglecting lateral flow of the groundwater, the thinning has led to an increase in saturated water storage of 39 mm yr^{-1}.

In terms of the water balance, evapotranspiration should have reduced considerably with the reduction in leaf area index from 1.9 to 0.6. This has been matched to a large extent by an increase in soil water storage.

The delayed response of groundwater level in the valley borehole could be due to a number of factors. The first is that thinning was not done in the forest around this borehole and the swamp area. Maybe it took a year for the rise in the groundwater table upslope to be reflected 50 m lower in the unthinned area. Another possible explanation is that water use of the swamp vegetation increased. Perhaps in the first year following thinning it had the capacity to use the extra soil water. But this was not so in the second year, particularly following the fire which reduced the leaf area index of this zone to virtually zero for some months. Following the fire in spring 1984 groundwater level in the valley borehole rose nearly two metres in comparison to control boreholes (figure 6.4).

The lack of further increases in groundwater level in the valley borehole in the third and fourth years could be due to a number of factors. Firstly, the surface soils are of a coarse to medium texture whereas the subsoils are much finer in texture. The surface soils will therefore have a higher soil water storage coefficient than the deeper soils. Thus even if the amount of water recharging the groundwater system remained the same as in previous years, the increase in groundwater level could be much less once the groundwater table reaches the surface soils. Secondly, there would be increased soil evaporation due to the elevated position of the groundwater table. The groundwater level in the valley borehole was less than one m below the surface for over two months in winter in the third year following thinning, and at a depth of less than two m for two months in winter in the fourth year following thinning. At other locations in the catchment the groundwater level may be closer to the ground surface than at the valley borehole location. Thirdly, there could be increased soil water use by swamp vegetation, particularly with the young leaves and relatively high leaf area index following the fire. Fourthly, there could be discharge of the groundwater to the stream. This is likely to have occurred to a greater extent in the third and fourth years following thinning because the groundwater level was closer to the surface (figure 6.4).

The temporal pattern of groundwater response following the 4L thinning is different to that observed following logging and regeneration in southern jarrah forest catchments. Borg *et al.* (1987a b) showed that groundwater levels increased rapidly for the first one to two years. Groundwater levels then increased more slowly for the next two to three years, followed by a four year steady decline in groundwater levels.

The different patterns in groundwater response from thinning compared with logging and regeneration are due to the different patterns in response of forest density. Stoneman *et al.* (1988b) reported that forest density recovered rapidly following logging and regeneration in the southern jarrah forest. Groundwater levels lower after about five years of regeneration. This corresponds with the age at which total cover is within 80 per cent or 90 per cent of unlogged values (Stoneman *et al.* 1989). However, following thinning, forest density does not recover rapidly if ground and stump coppice is controlled as in this experiment. Stoneman and Schofield (1989) reported that the leaf area index of a stand thinned to the same level as Yarragil 4L would still be approximately 50 per cent less after 21 years in comparison to an unthinned stand (figure 2.8).

Rising groundwater level is not of concern in the high rainfall zone where it normally leads to increases in fresh streamflows. However, it is of concern in the salt sensitive intermediate and low rainfall zones. Whether or not thinning results in stream salinity and potable water quality problems in these zones depends on a number of factors including:

(i) Whether groundwater will rise to the ground surface under thinning treatments.

(ii) The relative quantities and solute concentrations of groundwater, shallow throughflow and overland flow contributing to stream salinity.

(iii) Whether the resultant stream salinity significantly impacts the salinity of reservoirs.

The increases in streamflow following thinning have been relatively small in the first three years, averaging 12.3 mm yr^{-1}. However, because of the large soil water and groundwater storage capacities and the slow recovery in leaf area index following thinning it is likely that the peak response in streamflow is yet to occur. Therefore, further increases in streamflow from the Yarragil 4L catchment are likely.

Stoneman and Schofield (1989) have estimated that thinning of harnessed catchments in the northern jarrah forest will increase streamflow by at least 11.5 per cent of rainfall for the high and intermediate rainfall zones. They estimate a total potential streamflow increase from thinning of 127 million m^3 yr^{-1}. This is based on an estimated

1000 km^2 suitable for thinning, and a streamflow increase of 11.5 per cent of rainfall. This represents a 49 per cent increase in the long term mean annual streamflow. Of the potential streamflow increase, 48 million m^3 yr^{-1} would be utilised by the Perth Metropolitan Water Supply System. This would be a significant increase in the capacity of the system to meet future demand for water.

Chapter 7: General Discussion

Water and wood are two of the most important products from the northern jarrah forest. The efficiency of production of these two products and the effect of thinning on this efficiency is therefore important. A measure of this efficiency is "water use efficiency" which is the ratio of growth (G) to transpiration (E_t) (Viets 1962).

Chapter 5 provided data showing that thinning of the uneven-aged stands of the Yarragil 4L catchment increased stand growth. Chapter 6 presented the hydrologic evidence showing that thinning of the catchment increased streamflow and groundwater. What is the explanation for the simultaneous increase in water and wood production?

Cowan and Farquhar (1977) hypothesize that the ratio of change in plant growth to change in transpiration is constant and optimum. According to this hypothesis transpiration will increase in proportion to an increase in growth. If we calculate the catchment water balances before and after thinning using this assumption, then:

$$E_t = P - W - E_i + \Delta S + \Delta G$$

where E_t = transpiration

P = rainfall

W = streamflow

E_i = interception

ΔS = change in soil water

ΔG = change in groundwater

Before thinning (1976 - 1982):

where $P = 930$ mm

$W = 4$ mm

$E_i = 200$ mm (Stoneman and Schofield 1989)

$\Delta G = -28$ mm

$\Delta S = -28$ mm (assuming $\Delta S = \Delta G$)

Therefore:

$E_t = 782$ mm

which is equal to an average daily transpiration of 2.1 mm which seems reasonable for a forest with an LAI of 1.9 (Dunin and Mackay 1982).

After thinning (1985):

Growth increased by a factor of 1.94 (table 5.3).

Therefore, assuming that the change in transpiration is proportional to the change in growth:

$E_t = 1517$ mm and

where $P = 990$ mm

$W = 38$ mm

E_i = 67 mm (Stoneman and Schofield 1989)

ΔG = 39 mm

Solve for ΔS:

$$\Delta S = P - E_t - W - E_i - \Delta G$$
$$= - 671$$

Clearly this was not the case as groundwater levels increased, which indicates an increase in soil water, not a decrease in soil water. Additionally, Dunin and Mackay (1982) reported transpiration for eucalypt forest of a maximum of about 5 mm day^{-1} from stands with an LAI of 3. The transpiration of 1517 mm is equal to an average daily transpiration of 4.2 mm, which seems most unlikely for a forest with an LAI of 0.6.

To balance the water balance equation, transpiration must be less after thinning than above. Therefore, the hypothesis of Cowan and Farquhar (1977) does not hold. Water use efficiency has increased.

We do not have a direct measure of transpiration, so it is difficult to calculate the water use efficiency. However, we can calculate water use efficiency based on two separate assumptions. Firstly, we can assume that reductions in transpiration are proportional to reductions in leaf area (McNaughton and Jarvis 1983).

1. Before thinning:

E_t = 782 mm (from previous calculation)

WUE = G / E_t

where G = 0.98 m^3 ha^{-1} * 830 kg m^{-3} (Brennan and Doust 1988)

WUE = 1.04 kg ha^{-1} mm^{-1}

1. After thinning:

E_t = 782 mm * (0.6 / 1.9)

= 247 mm

where G = 1.90 m^3 ha^{-1} * 830 kg m^{-3}

WUE = 6.38 kg ha^{-1} mm^{-1}

Based on this assumption there is a six fold increase in water use efficiency.

The second assumption is that soil water changes by the same amount as groundwater after thinning. This assumption seems reasonable based on the data of Williamson *et al.* (1987) who reported that ΔS was similar to ΔG in most years, except in the first year following the clearing of Wights catchment.

2. Before thinning:

The water balance is the same as previously calculated.

$$\text{WUE} = 1.04 \text{ kg ha}^{-1} \text{ mm}^{-1}$$

2. After thinning:

$$E_t = P - W - E_i + \Delta S + \Delta G$$

$$= 990 - 38 - 67 + 39 + 39$$

$$= 963 \text{ mm}$$

$$\text{WUE} = 1.64 \text{ kg ha}^{-1} \text{ mm}^{-1}$$

Based on this assumption there is a sixty per cent increase in water use efficiency. The actual transpiration and water use efficiency after thinning is probably between the two values calculated above. Therefore, water use efficiency has increased by between a factor of 1.6 and six.

In practical terms, water use efficiency could be calculated using merchantable stand growth, and including interception with transpiration in the water loss. This will also show large increases in water use efficiency after thinning. Therefore, both transpiration efficiency (growth / transpiration) and evapotranspiration efficiency (growth / evapotranspiration) (Tanner and Sinclair 1983) are increased by thinning. This contrasts the results from agricultural crops (Ritchie 1983; Tanner and Sinclair 1983). However, agricultural crops are even-aged and their water use efficiency changes with age (Doorenbos and Kassam 1978 cited by Stanhill 1986). Therefore, changes in age structure of agricultural crops may change their water use efficiency.

The increase in water use efficiency after thinning is attributed to the reduction in competition. This is because the younger and more vigorous retained trees (see Section 4.6) responded particularly well to the reduction in competition. This is reflected in figure 7.1 where the increase in water use efficieny due to thinning is greatest in the smaller size classes.

In summary, the simultaneous increases in water production and wood production indicate an increase in water use efficiency at the catchment scale. This increase in water use efficiency is attributed to the reduction in competition and the response of the relatively young and vigorous retained trees which have a greater increase in water use efficiency than the older trees when released from competition.

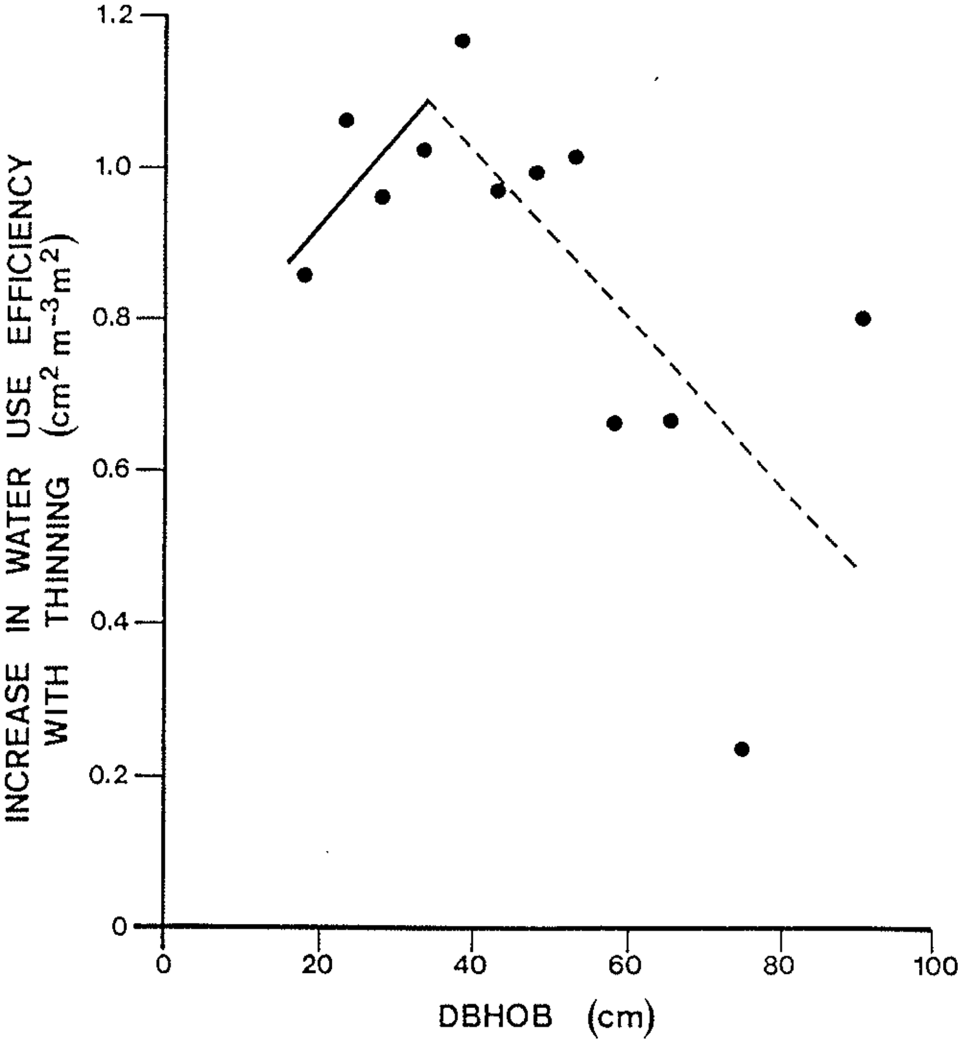

Figure 7.1: Increase in tree water use efficiency in response to thinning for a range of tree size classes in the Yarragil 4L catchment. The water use efficiency was calculated for the thinned and unthinned trees in each size class using (i) the mean basal area over bark growth of the size class, (ii) the leaf area corresponding to the midpoint of the size class using the equation of Carbon *et al.* (1979) and (iii) assuming that transpiration was proportional to leaf area both before and after thinning at the rate of 0.4116 m^3 m^{-2} (equal to 782 mm of transpiration for a leaf area index of 1.9).

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Appendix A: Description of Yarragil 4L and Surrounds

A number of geomorphic, topographic and vegetation characteristics of the area have been calculated. These aid in evaluating the representativeness of the 4L catchment.

1. Landform

Landforms were mapped by McArthur *et al.* (1977) from aerial photography with ground checking. A description of the various landform units represented in the Yarragil catchment follows.

Dwellingup: Lateritic upland with a gently undulating landscape. Duricrust on ridges; sands and gravels in shallow depressions.

Yarragil: Minor valleys of the western part of the Darling plateau. Sandy gravel on the slopes; orange earths in swampy floors.

Murray: Deeply incised major valleys with red and yellow earths on slopes; narrow alluvial terraces.

Rock: Rocky areas.

The 4L catchment is very much an extreme catchment with 81 per cent being in the Dwellingup landform. The only other catchments which come close are 4D and 9A with 68 per cent. Most of the other catchments have around 50 per cent Dwellingup landform. The 13 and 11A catchments are the only two with any Murray landform, with 50 per cent and 49 per cent respectively (table A 1).

2. Soils

Soil types represented in the Yarragil catchment are:

LD: laterite dominated by duricrust, generally on ridges.

LD: laterite dominated by gravels, generally in depressions.

GS: slopes with detrital gravels, up to 3 m deep.

A: erosional alcoves which are steep narrow gullies often with rock outcropping.

SV: sandy upland valley at the heads of drainage lines.

VV: narrow deep valleys in laterite.

SF: gently sloping sandy fringe at foot of slope.

RE: steep irregular slopes with red and

Table A 1: Percentage of catchment areas in each landform for Yarragil 4L and control catchments

CATCHMENT	LANDFORM			
	MURRAY	YARRAGIL	DWELLINGUP	ROCK
4L	0	19	81	0
13	50	0	39	11
11A	49	0	51	0
4K	0	53	47	0
4E	0	54	46	0
4T	0	42	58	0
4P	0	46	54	0
4D	0	32	68	0
4X	0	35	65	0
5D	0	49	51	0
6C	0	44	56	0
9A	0	32	68	0
10B	0	46	54	0

yellow earths and some rock outcrops.

SW: valley floor with various deposites and often swampy in the upper reaches.

The 4L catchment is an extreme catchment in terms of soils types, with 94 per cent of the catchment in the LD and LG soils types. Most other catchments have a lot more of the GS and SV soils. Catchments 13 and 11A also have significant areas of RE. The soil types are telling us, as did the landform, that the 4L catchment is very much an upland (table A 2).

3. Slopes

Catchment 4L has mild slopes in comparison to others, with 97 per cent in the classes < 3. The 10B catchment has 96 per cent, 4E has 94 per cent, and 9A has 93 per cent in these slope classes. 13 has the steepest slopes, and 11A the second steepest. The 4T, 4P and 4X catchments are the steepest of the remaining catchments. An approximate rating of the catchments from least steep to most steep is: 4L, 10B, 4E, 9A, 6C, 4D, 5D, 4K, 4X, 4P, 4T, 11A and 13 (table A 3).

Table A 2: Percentage of catchment areas in each soil type for Yarragil 4L and control catchments.

CATCHMENT	SOIL TYPE								
	LD	LG	GS	A	SV	VV	SF	RE	SW
4L	22	72	0	0	0	0	0	0	6
13	16	26	3	0	0	0	0	55	0
11A	17	44	15	5	0	0	2	17	0
4K	21	56	12	0	0	0	0	0	11
4E	31	50	14	0	0	0	0	0	5
4T	23	28	32	0	9	0	0	0	9
4P	25	18	28	0	20	0	0	0	9
4D	16	20	50	0	9	0	0	0	5
4X	20	32	22	0	19	0	0	0	7
5D	24	17	11	0	42	0	0	0	6
6C	19	22	24	0	21	7	0	0	7
9A	33	34	21	0	9	0	0	0	3
10B	18	23	22	0	31	0	0	0	6

Table A 3: Percentage of catchment areas in each slope class for Yarragil 4L and control catchments.

CATCHMENT	SLOPE							
	1	2	3	4	5	6	7	8
4L	2	31	64	3	0	0	0	0
13	0	3	3	29	50	15	0	0
11A	0	2	15	63	20	0	0	0
4K	0	9	77	14	0	0	0	0
4E	0	22	72	6	0	0	0	0
4T	3	15	53	22	1	5	0	0
4P	0	8	69	23	0	0	0	0
4D	1	33	51	15	0	0	0	0
4X	0	20	55	24	1	0	0	0
5D	0	20	66	14	0	0	0	0
6C	2	31	53	14	0	0	0	0
9A	7	54	31	7	0	0	0	0
10B	12	55	29	4	0	0	0	0

4. Forest Structure and Height Class

Forest structure and height class were mapped by the Forests Department from aerial photography taken in November 1958. The maps were interpreted and compiled in 1961 and 1962. Three forest structures are found in the Yarragil catchment:

Massed:	where a high density of all size classes of trees enter the upper canopy level.
Pole:	where the upper canopy level is clearly separable from the pole understorey.
Sapling:	where there is an upper canopy level of large trees with an understorey of saplings or shrubs.

Three height classes are also found in the Yarragil catchment:

A:	25m - 29m
B+:	20m - 24m
B:	15m - 19m

The four slightly lower rainfall catchments have greater amounts of lower quality forest (i.e. B+ height class) than the other catchments. Most catchments have 50 per cent or 60 per cent poles.

However, 9A, 5D, 4X and 10B have more pole stands, with 83 per cent, 81 per cent, 78 per cent and 73 per cent respectively. The 4L catchment appears fairly typical with 59 per cent pole A and 33 per cent massed A (table A 4).

5. Logging History

Various parts of the catchment have been logged over once, twice or three times from prior to 1920 up to 1980. A brief description of when logging took place in each catchment follows:

13: Logged once between 1930-1935

11A: Logged once between 1930-1935

4K: Logged between 1923-1930 and again between 1935-1940. Parts were logged a third time between 1970-1980 and converted to eucalypt plantations.

4L: Logged between 1923-1930 and again between 1935-1940.

4E: Logged between 1923-1930 and again between 1935-1940.

4T: Logged between 1923-1930 and again between 1935-1940.

4P: Logged between 1923-1930 and again between 1935-1940.

Table A 4: Percentage of catchment areas in each forest structure and height class for Yarragil 4L and control atchments

CATCHMENT	FOREST STRUCTURE AND HEIGHT CLASS					
	POLE A	POLE B+	POLE B	MASSED A	MASSED B+	SAPLING B+
4L	59	0	0	33	0	8
13	55	0	0	45	0	0
11A	51	10	0	39	0	0
4K	62	0	0	29	0	9
4E	55	0	0	42	0	3
4T	31	0	0	56	0	13
4P	51	0	0	32	0	17
4D	65	0	0	28	0	7
4X	78	0	0	15	0	7
5D	62	19	0	7	1	11
6C	39	15	0	40	0	6
9A	74	9	0	27	0	9
10B	38	47	0	4	1	9

4D: Partly logged between 1935-1945 and the remainder logged between 1950-1960.
4X: Partly logged between 1935-1945 and the remainder logged between 1950-1960.
5D: Logged between 1923-1930 and partly logged again between 1950-1960.
6C: Logged between 1923-1930 and again between 1935-1940.
9A: Partly virgin forest. Partly logged once between 1923-1930. Remainder logged 1923-1930 and again 1935-1940.
10B: Partly logged prior to 1920. Remainder logged 1950-1960.

6. Dieback

Jarrah dieback was mapped by the Forests Department from 70 mm colour aerial photography taken in autumn 1978 and 1979. The photography was interpreted in October 1980. The proportion of a catchment which is dieback-free ranges from 76 per cent for 4K to 96 per cent for 4X and 5D. The 4L catchment was slightly more dieback-free forest than the average with 92 per cent. Dieback in the Yarragil catchment occurs almost exclusively on the lowlands (table A 5).

Table A 5: Percentage of catchment areas in each dieback class for Yarragil 4L and control catchments

CATCHMENT	DIEBACK OCCURRENCE	
	DIEBACK-FREE	DIEBACK
4L	92	8
13	NA	NA
11A	NA	NA
4K	76	24
4E	81	19
4T	89	11
4P	88	12
4D	92	8
4X	96	4
5D	96	4
6C	90	10
9A	93	7
10B	92	8

7. Crown Cover

Crown cover was interpreted from 1:25,000 scale black and white aerial photography flown in 01 & 02/1976.

Crown cover ranges from 37 per cent for 4K to 55 per cent for 13, with 4L being on the lower side of average with 42 per cent (table A 6).

8. Catchment Area

Catchment area (A) was determined from 1:25,000 maps with 10 m contour intervals.

The 4L catchment is the sixth smallest of the 13 catchments being 126 ha in area. At 66 ha 4K is the smallest catchment and 9A with 618 ha is the largest. Catchment size generally increases from west to east (table A 6).

9. Latitude and Longitude

The 4L catchment is the fourth most western catchment after 13, 11A and 4K. The most eastern catchments are 10B, 9A and 5D (table A 6).

Table A 6: Catchment area, crown cover, latitude and longitude of Yarragil 4L and control catchments

CATCHMENT	AREA (ha)	CROWN COVER (%)	LATITUDE	LONGITUDE
4L	126	42	50 55	11 25
13	71	55	48 51	9 18
11A	79	50	49 7	10 8
4K	66	37	50 47	11 23
4E	123	42	50 39	12 8
4T	311	45	51 35	12 47
4P	140	44	51 40	12 55
4D	244	47	50 40	13 9
4X	270	51	50 34	13 19
5D	402	41	50 7	14 15
6C	490	43	49 26	13 39
9A	618	45	47 53	15 2
10B	566	49	48 47	15 35

10. Weir Elevation

With a weir elevation of 280 m above sea level 4L is one of the highest catchments. Other catchments with similar weir elevations are 4K, 4T, 4P, 9A and 10B. 13 and 11A which are down in the steep valley are the lowest at 180 m and 190 m above sea level respectively (table A 7).

11. Catchment Morphology

A number of measures of catchment morphology have been made for each catchment. The definitions below are from Langford and O'Shaughnessy (1977) and Gregory and Walling (1973).

(i) Circularity Ratio (C) is defined, following Miller (1953), as the ratio of the area of the catchment to the area of a circle having the same perimeter
i.e. $C = 4 \quad A/P^2$
where A = catchment area and P = catchment perimeter.

(ii) Catchment "lid" aspect and slope were determined, following Lee (1963). A surface through equally spaced points on

Table A 7: Weir elevation, perimeter length and circularity ratio of Yarragil 4L and control catchments.

CATCHMENT	WEIR ELEVATION A.S.L. (m)	PERIMETER LENGTH (m)	CIRCULARITY RATIO
4L	280	5300	0.54
13	180	3310	0.81
11A	190	4100	0.58
4K	283	3310	0.78
4E	245	5080	0.60
4T	280	7350	0.69
4P	283	4380	0.80
4D	257	7610	0.53
4X	258	6670	0.75
5D	263	8390	0.62
6C	240	9580	0.67
9A	280	13510	0.42
10B	280	13290	0.40

the catchment perimeter is statistically fitted. These points are defined in terms of a three co-ordinate system.

(iii) Maximum Vertical Relief is defined, following Strahler (1952), as the difference in elevation between the highest and the lowest points in the catchment.

(iv) Main Valley Axis descriptors are defined following Schumm (1956) and involving a subjective decision as to the orientation of the principal drainage line.

* Length (L) is the horizontal distance along the longest dimension of the basin parallel to the principal drainage line.

* The true bearing (B) is (measured in degrees clockwise from north) of the principal drainage line taken at the point of intersection with the weir. By taking back bearings, downslope orientations of the principal valley axes are obtained which can be compared with the catchment "lid" aspects.

* Vertical relief (H) is along the longest dimension of the basin parallel to the principal drainage line i.e. parallel to L above.

Relief ratio is H/L.

(v) Relative relief is defined, following Melton (1957), as the ration H/P.

(vi) Elongation Ratio (E) is defined, following Schumm (1956), as the ratio of the diameter of a circle with the same area as the catchment to the catchment length:

i.e. $$E = \frac{2 \sqrt{(A/\pi)}}{L}$$

(vii) Form Factor (F) is defined, following Horton (1932), as the ratio A/L^2.

(viii) Main Channel Length was determined from 1:25,000 scale maps, with some ground checks.

(ix) Drainage Density is defined, following Horton (1932), as the length of stream per unit of catchment area (km/km^2).

(x) Main Channel Relief is defined as the difference in elevation between the weir and the source of the mainstream.

(xi) Main Channel Gradient is defined, following Lane *et al.* (1975). It is the slope of the right triangle hypotenuse with the same stream length and the same area as the area under the stream profile.

Catchment shape is characterised by the circularity ratio, the elongation ratio and the form factor. Catchments 13, 4P and 4K have the highest circularity ratio and are the roundest catchments. The least round catchments are 10B, 9A, 4D and 4L. The relatively low elongation ratio's and form factor's for 11A and 4E indicate the relative elongation of these catchments. Catchments 6C and 4T have higher elongation ratio's and form factor's. They are relatively shorter and wider catchments (Tables A 7 and A 10).

Table A 8: Aspect and slope of the catchment lid, and maximum vertical relief of Yarragil 4L and control catchments.

CATCHMENT	CATCHMENT LID ASPECT (°)	SLOPE (°)	MAXIMUM VERTICAL RELIEF (m)
4L	166	3.1	75
13	154	8.8	170
11A	222	4.5	150
4K	247	1.4	57
4E	162	2.6	95
4T	153	1.2	86
4P	210	12.9	83
4D	160	2.0	113
4X	119	2.0	102
5D	144	2.1	87
6C	99	0.4	81
9A	355	0.2	70
10B	143	0.3	66

Table A 9: Length, vertical relief, bearing and relief ratio of the main valley axis of Yarragil 4L and control catchments.

CATCHMENT	MAIN VALLEY AXIS LENGTH (m)	VERTICAL RELIEF (m)	BEARING (°)	RELIEF RATIO
4L	1100	50	220	0.045
13	1250	160	194	0.128
11A	1375	130	201	0.095
4K	900	38	287	0.042
4E	1750	75	183	0.043
4T	1775	70	148	0.039
4P	1625	67	158	0.041
4D	1500	67	171	0.045
4X	2500	82	107	0.033
5D	2500	67	76	0.027
6C	2525	70	72	0.028
9A	4550	60	40	0.013
10B	3375	42	220	0.012

Table A 10: Relative relief, elongation ratio, form factor and main channel length of Yarragil 4L and control catchments.

CATCHMENT	RELATIVE RELIEF	ELONGATION RATIO	FORM FACTOR	MAIN CHANNEL LENGTH (m)
4L	0.009	0.011	0.054	600
13	0.048	0.008	0.028	375
11A	0.032	0.007	0.028	875
4K	0.011	0.010	0.038	525
4E	0.015	0.007	0.035	1580
4T	0.010	0.011	0.083	2775
4P	0.015	0.007	0.038	1650
4D	0.009	0.012	0.081	1050
4X	0.012	0.007	0.053	1900
5D	0.008	0.008	0.070	1800
6C	0.007	0.010	0.097	3750
9A	0.004	0.006	0.067	3425
10B	0.003	0.008	0.084	3500

Drainage density for all of the catchments is very low, falling into the category defined as "coarse" by Strahler (1957). The 4D, 4L and 13 catchments have the lowest drainage densities. Catchments 4P, 11A and 4T have the highest drainage densities (table A 8).

All of the catchment "lids" have a southerly aspect, except 9A. The 4K catchment has the most westerly aspect and 6C the most easterly. Catchments 9A and 10B have the flattest catchment "lid" inclination with slopes of 0.2° and 0.3° respectively. Catchments 4P and 13 have the steepest "lids" with slopes of 12.9° and 8.8° respectively (table A 8).

Relief ratio and relative relief give an indication of slopes in the catchment. Catchments 9A and 10B have the lowest relief ratio's and relative relief. They are the flattest catchments. Catchments 13 and 11A have the highest relief ratio's and relative relief. They are the steepest catchments (Tables A 9 and A 10).

Table A 11: Drainage density, and main channel relief and gradient, of Yarragil 4L and control catchments.

CATCHMENT	DRAINAGE DENSITY km/km^2	MAIN CHANNEL RELIEF (m)	MAIN CHANNEL GRADIENT (°)
4L	0.50	21	2.01
13	0.53	63	9.67
11A	1.12	55	3.60
4K	0.77	15	1.64
4E	1.28	45	1.92
4T	0.94	37	0.76
4P	1.35	34	1.18
4D	0.43	43	2.35
4X	0.72	29	0.88
5D	0.52	34	1.08
6C	0.76	47	0.72
9A	0.56	37	0.62
10B	0.62	22	0.36

12. Rainfall

Average annual rainfall for the study period (1976-1985) was below average. Rainfall varies from a long term (1926-1979) average annual of 1160 mm in the most westerly catchment i.e. 13, to 1020 mm in the most easterly catchment, i.e. 10B (table A 12). The 4L catchment has a long term average annual rainfall of 1120 mm.

13. Streamflow

Streamflows range from 4.3 mm or 0.5 per cent of rainfall for 4L, to 50.9 mm or 5.5 per cent of rainfall for 4E (table A 12). Long term average annual streamflow could be expected to be substantially greater than the average for the study period. In 1983, a year with slightly more than average rainfall, 4L had 21.3 mm or 1.9 per cent streamflow and 4E had 135.7 mm or 11.8 per cent streamflow. Long term average annual streamflow could be expected to be greater than in 1983. This is because 1983 was preceded by nearly a decade of below average rainfall years. Therefore, in 1983 a greater proportion of rainfall than average would go to recharging soil water stores and less to streamflow.

Table A 12: Long term average annual rainfall, average annual rainfall and average annual streamflow for the study period for Yarragil 4L and control catchments.

[1] = 1976-1982
[2] = 1976-1984
[3] = 1980-1985

CATCHMENT	AVERAGE ANNUAL RAINFALL 1976-1985 (mm)	LONG TERM AVERAGE ANNUAL RAINFALL 1926-1979 (mm)	AVERAGE ANNUAL STREAMFLOW 1976-1985 (mm)
4L	932	1120	4.3[1]
13	983	1160	19.9[2]
11A	956	1150	27.2
4K	933	1120	20.7
4E	930	1100	50.9
4T	938	1080	36.6
4P	938	1080	42.1[2]
4D	942	1080	14.6[1]
4X	918	1070	15.3
5D	888	1040	11.2
6C	878	1060	8.5
9A	866	1030	5.2[2]
10B	834	1020	15.8[3]

Appendix B: Characteristics of Vegetation Types in the Yarragil 4L Catchment (from Havel 1975)

Vegetation type P

Indicator species: *Lepidosperma angustatum, Lechenaultia biloba, Allocasuarina fraseriana, Grevillea wilsonii, Styphelia tenuiflora, Patersonia rudis, Acacia strigosa, Banksia grandis, Adenanthos barbigera, Hovea chorizemifolia, Personia longifolia* and less consistently *Davesia pectinata, Hakea ruscifolia, Lasiopetalum floribundum, Phyllanthus calycinus, Trymalium ledifolium.*

Tree statum:

(i) General: Moderately tall, dense stand.

(ii) Basal area (m^2 ha^{-1}): Range 18-78, mean 40.

(iii) Height (m): Range 24-35, mean 29.

(iv) Composition: Overwhelmingly *Eucalyptus marginata* with occasional *Eucalyptus calophylla*; strong development of second storey of *Allocasuarina fraseriana* and *Banksia grandis*.

Topographic and geographic position:

(i) Curvature: Mostly uniform.

(ii) General: Mild, lower and middle slopes.

(iii) Slope (degrees): Range 0-12, mean 4.

(iv) Rock outcrops: Moderately frequent occurence of isolated lateritic ironstone outcrops.

Soil:

(i) General: Lateritic gravel with sand or loamy sand matrix, or sand with heavy gravel.

(ii) Physical properties (topsoil):

- (a) Gravel (%): Range 15-73, mean 55.
- (b) Silt + clay (%): Range 4-18, mean 8.
- (c) Depth to water table (cm): >> 90.
- (d) Field capacity (%): Range 5-11, mean 7.
- (e) Wilting point (%): Range 2-6, mean 3.
- (f) Available moisture (%): Range 2-5, mean 3.

(iii) Chemical properties (topsoil):

- (a) pH: Range 5.4-7.1, mean 6.1.
- (b) N (%): Range 0.01-0.14, mean 0.06.
- (c) P (ppm): Range 12-100, mean 35.
- (d) K (me%): Range 0.05-0.99, mean 0.30.
- (e) Exch. Ca (me%): Range 0.5-8.9, mean 3.5.
- (f) Exch. Mg (me%): Range 0.4-3.4, mean 1.0.
- (g) C.E.C (me%): Range 2.2-21.7, mean 8.4.
- (h) Saturation (%): Range 11-78, mean 54.

Broad description: Gravelly sands and sandy gravels, occuring on mid and lower slopes in medium and high rainfall zone.

Vegetation type T

Indicator species: *Leucopogon verticillatus, Pteridium esculentem, Clematis pubescens, Macrozamia riedlei, Leucopogon capitellatus, Leucopogon propinquus, Phyllanthus calycinus, Acacia urophylla, Lasiopetalum floribundum, Bossiaea aquifolium* and less consistently *Chorizema ilicifolium, Banksia grandis, Adenanthos barbigera, Eucalyptus patens, Styphelia teniflora, Acacia strigosa, Patersonia rudis, Hakea lissocarpha.*

Tree statum:

(i) General: Tall, dense stand.

(ii) Basal area (m^2 ha^{-1}): Range 26-44, mean 35.

(iii) Height (m): Range 29-39, mean 33.

(iv) Composition: *Eucalyptus marginata* with moderate admixture of *Eucalyptus calophylla*, in few plots with *Eucalyptus patens*, second storey of *Banksia grandis*, *Personia longifolia.*

Topographic and geographic position:

(i) Curvature: Mainly convex.

(ii) General: Upper slopes and ridges in strongly dissected, high rainfall western zone.

(iii) Slope (degrees): Range 2-15, mean 7.

(iv) Rock outcrops: Heavy massive lateritic ironstone , occasional granite and epidiorite.

Soil:

(i) General: Orange to brown gravel with sandy loam to loam matrix, in a few marginal cases loam with medium gravel.

(ii) Physical properties (topsoil):

- (a) Gravel (%): Range 3-84, mean 44.
- (b) Silt + clay (%): Range 9-46, mean 25.
- (c) Depth to water table (cm): >> 90.
- (d) Field capacity (%): Range 11-23, mean 16.
- (e) Wilting point (%): Range 5-14, mean 8.
- (f) Available moisture(%): Range 5-11, mean 8.

(iii) Chemical properties (topsoil):

- (a) pH: Range 5.8-6.9, mean 6.1.
- (b) N (%): Range 0.06-0.30, mean 0.14.
- (c) P (ppm): Range 10-188, mean 89.
- (d) K (me%): Range 0.20-1.04, mean 0.60.
- (e) Exch. Ca (me%): Range 2.3-14.7, mean 7.3.
- (f) Exch. Mg (me%): Range 1.2-5.8, mean 2.5.
- (g) C.E.C (me%): Range 6.5-25.9, mean 14.8.
- (h) Saturation (%): Range 45-80, mean 70.

Broad description: In the northern portion of the jarrah forest, this segment is very much restricted to the slopes of the strongly dissected high rainfall western zone. By contrast, it is more broadly distributed in the southern portion.

Vegetation type W

Indicator species: *Lepidosperma angustatum, Mesomelaena tetragona, Synaphea petiolaris, Hakea lissocarpha, Hypocalymma angustifolium, Eucalyptus patens, Acacia extensa* and less consistently *Leptocarpus scariosus, Leptospermum ellipticum, Dampiera alata.*

Tree statum:

(i) General: Moderately dense of medium height.

(ii) Basal area (m^2 ha^{-1}): Range 24-54, mean 33.

(iii) Height (m): Range 18-32, mean 27.

(iv) Composition: Equal admixture of *Eucalyptus marginata, Eucalyptus calophylla* and *Eucalyptus patens.*

Topographic and geographic position:

(i) Curvature: Concave.

(ii) General: Lower slopes and valley floors.

(iii) Slope (degrees): Range 1-4, mean 3.

(iv) Rock outcrops: Rare, occassionally granite.

Soil:

(i) General: Yellow-brown or orange-brown sandy loams to loams occasionally with lateritic gravel, especially in the subsoil.

(ii) Physical properties (topsoil):

- (a) Gravel (%): Range 0-26, mean 14.
- (b) Silt + clay (%): Range 13-20, mean 12.
- (c) Depth to water table (cm): 27-90.
- (d) Field capacity (%): Range 3-35, mean 16.
- (e) Wilting point (%): Range 1-12, mean 6.
- (f) Available moisture(%): Range 1-22, mean 9.

(iii) Chemical properties (topsoil):

- (a) pH: Range 5.5-6.3, mean 6.0.
- (b) N (%): Range 0.05-0.34, mean 0.14.
- (c) P (ppm): Range 12-66, mean 36.
- (d) K (me%): Range 0.25-0.86, mean 0.58.
- (e) Exch. Ca (me%): Range 1.0-6.4, mean 3.5.
- (f) Exch. Mg (me%): Range 0.7-5.4, mean 1.9.
- (g) C.E.C (me%): Range 7.0-23.0, mean 10.6.
- (h) Saturation (%): Range 33-67, mean 55.

Broad description: Moist sandy loams on lower slopes and valley floors, with tendency to excessive wetness in winter.

Appendix C: Specification For Crop Tree Retention

For the purposes of this prescription the idealised crop tree is described as a tree which occurs in or above the general level of the canopy of the group of surrounding trees, has a healthy, vigorous crown and a straight defect free bole. It should have the capacity to grow for many years i.e. to be available in the future crop whether that be in five or 50 years hence. Due to the nature of the forest, size and age of the crop trees will be variable, ranging from sapling through to mature tree.

Where there is a surplus of trees meeting the specifications of the idealised crop tree the highest value product should be removed. Where there is a deficit of trees meeting the specifications of the idealised crop tree, the best quality trees should be selected and marked for retention, so that the specified canopy cover is retained. The preferred species is jarrah, but some marri, sheoak and blackbutt should always be retained.

Crop trees are to be selected on the basis of the above description and at a spacing dependent on the average dbhob of the trees to be retained in the particular group being marked. The table below (table C 1) shows the number of trees ha^{-1} and the spacing required for the average dbhob of the trees to be retained.

Table C 1: Spacing and stocking of trees to be retained in the thinning of the Yarragil 4L catchment depending on their average dbhob.

Average dbhob (cm)	Stocking (stems ha^{-1})	Spacing (m)
10	475	4.5
20	325	5.5
30	200	7.0
40	135	8.5
50	100	10.0
60	75	11.5