Forest Management to Increase Water Yield from the Northern Jarrah Forest

A report by the Steering Committee
for Research on Land Use and Water Supply

Water Authority of Western Australia
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Foreword

Future development of the Perth-Bunbury region is reliant on the provision of water supplies at an appropriate quality and acceptable cost. Most of the readily accessible, lower cost, potable water resources in this region are already utilized, and the demand for land and water resources has risen to a level where there is a significant incidence of competition between uses. It is also recognised that water resource planning must take into account non-consumptive uses such as conservation of important environments and recreation.

Even with a demand management programme aimed to reduce the rate of increase in water consumption, population growth will result in a significant increase in water supply requirements over the next few decades. Furthermore, there is now significant scientific consensus that south-western Australia will experience a gradual shift to a drier climate over the next 30 to 50 years. Thus the possible depletion of current resources, increasing demand, and increasing competition for the remaining water resources, will make further water supply developments necessary and substantially more expensive.

Considering this future brings into sharp focus a need to increase the water yield of already developed water supply catchments. The potential to increase the water yield of these catchments through forest management has been under consideration for some years. Experimental catchments were established in the Dwellingup area with the specific purpose of developing the necessary understanding of the relationship between forest management practices and water yield. This research is still at an early stage but there is now sufficient information available for the Research Steering Committee to indicate the order of possible yield increases and to discuss the management implications.

K L Barrett

Chairman, Steering Committee for Research on Land Use and Water Supply

Contents

List of Figures

List of Tables

Acknowledgements

The gathering and assessment of hydrologic and silvicultural data necessary for the improved management of the forest region of the south-west depends on the work of many people from various disciplines and organisations. The dedication and skills of these people are gratefully acknowledged. For the preparation of this report the Steering Committee expresses its gratitude to Dr N. J. Schofield, Mr J. R. Bartle and Mr G. L. Stoneman.

1. *Executive Summary and Recommendations*

Introduction

Historically, the continuing growth in demand for water to supply the Perth Metropolitan Area has been met by the development of new sources. With the more readily accessible water supply sources already used, future developments will be increasingly expensive. This report looks at the option of increasing the flow into existing reservoirs through forest thinning as a means of minimising the need for further developments.

Reduction of forest density could be implemented by established silvicultural practices. These practices have been developed mainly to increase timber production. The practice of 'thinning out' small and inferior stems increases the growth rate of the superior stems and produces a greater utilizable timber yield. Thinning has not been widely carried out in the jarrah forest as it is only marginally economically viable for timber production alone. This report reviews the possible use of thinning, in combination with other silvicultural practices, to produce significant increases in water yield at low cost, while at the same time being beneficial to timber production.

Logging history and silvicultural treatments

Over a century of logging has converted the old growth jarrah forest into a forest dominated by relatively young, dense regrowth. The proportion of regrowth in any area reflects 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 mixed-aged stands. Both types of stand are overstocked, exhibiting low growth rates on individual stems and high water use by the whole stands.

Appropriate silvicultural treatments are well established. The objective is to create more open stands of selected crop trees. The target stocking density is 10 m^2/ha of tree basal area. This stocking density retains full areal timber production potential but doubles the growth rate of the crop trees. Even-aged stands will usually have enough crop trees for direct thinning. Mixed-aged stands commonly have less crop trees and need to go through a felling and regeneration treatment before being thinned.

A programme of forest thinning to increase water production would need to be incorporated into the planning of forest operations. These operations must be integrated with fire management, bauxite mining and dieback management. A lead time of several years would be required for preparing plans for the adoption of catchment-scale forest thinning for water production.

Areas available for silvicultural treatment

A preliminary survey of areas suitable for silvicultural treatment in the current water supply catchments has been completed. In the high rainfall zone (annual rainfall greater than 1100 mm per year), it is estimated that about 460 square kilometres are available, and it is estimated that about 540 square kilometres are potentially suitable in the intermediate rainfall zone (annual rainfall between 900 mm and 1100 mm per year) . These estimates have been derived from broad-scale forest information and probably represent a slight over-estimation. A detailed inventory of forest attributes is necessary to refine these figures.

Water yield increases and associated costs

Streamflow in the jarrah forest region is an unusually low proportion of rainfall. Forest thinning will increase streamflow but catchment experiments to measure the size of the increase will not be conclusive for several years. In the absence of direct data, indirect estimates of streamflow response to forest thinning have been made. Three sources of information were examined, namely various forest treatments on research catchments, canopy cover-streamflow relationships and model simulations. The three estimates derived were found to be reasonably consistent despite the low reliability of each estimate. In the high rainfall zone, the estimated increase in streamflow ranged between 138 and 218 mm (11.5%-18.2% of rainfall). In the intermediate rainfall zone, the estimated range was 115-119 mm (11.5%-11.9% of rainfall). It should be emphasised that these estimates will be subject to uncertainty until the results of research become available over the next few years.

Applying the lowest estimated streamflow increase to the areas of water supply catchments estimated to be suitable for thinning treatment, indicates a total potential streamflow volume increase of 127 million cubic metres. This is 47% above the current average annual streamflow volumes of the major water supply catchments. The potential streamflow volume increase is about equally divided between the high rainfall zone and the intermediate rainfall zone.

Of the 127 million cubic metres increased streamflow, only 48 million cubic metres would be utilized by the Metropolitan Water Supply System because of spillage, evaporation, trunk main capacity and other factors. If the trunk mains were upgraded, the amount of streamflow utilised by the Water Supply System would rise to 64 million cubic metres. If only the high rainfall zone was treated, 37 million cubic metres would be utilized by the present Water Supply System.

The cost of producing the estimated total utilizable water yield would range from 2.3 to 7.9 cents per cubic metre, depending on the method of silvicultural treatment and utilization of the products from thinning. For the high rainfall zone only, the cost range would be from 1.4 to 4.7 cents per cubic metre. In both cases, the cost compares favourably with the alternative of developing new sources at a minimum cost of 20 cents per cubic metre.

The proposition of silviculture for water production is considerably more attractive in the high rainfall zone than the intermediate rainfall zone because of faster response, more water yield per unit area thinned, lower cost, and the absence of stream salinity concerns.

Implications and uncertainties

Forest thinning clearly has considerable potential to economically increase the water yield from existing jarrah forest catchments. However, several uncertainties remain to be resolved before this potential can be fully developed. The major areas of future study are outlined below.

(i) More reliable estimates of potential streamflow increases across the region are required.

(ii) More detailed information is required on areas available for silvicultural treatment and the distribution of the attributes which determine the different silvicultural methods that would be used. Combined with better estimates of potential streamflow increases, this would assist a detailed cost-benefit analysis and facilitate the integration of the new practices into forest and water resources planning and management.

(iii) Bauxite mining is planned to continue within the northern jarrah forest for the next 70 years or more. It is therefore necessary to jointly plan forest silviculture and mining to avoid premature mining of silviculturally treated areas. In addition minesite rehabilitation methods and silvicultural treatment of revegetated pits should be studied.

(iv) The dieback fungus (*Phytophthora cinnamomi*) may be favoured in the moister environment likely to be generated under extensive thinning. This problem could be largely contained by applying standard disease management practices but it highlights the importance of current research which aims to better understand dieback and to devise more advanced control methods.

(v) Forest thinning in the intermediate rainfall zone may result in the salinity of some streams increasing to unacceptably high levels. This would occur in areas of high salt storage and where groundwater had risen to the ground surface. If extensive thinning is to be carried out in the intermediate rainfall zone, simple techniques would be required to identify areas where streamflow increase can be achieved with acceptable stream salinities.

(vi) Forest thinning has the potential to increase peak streamflows and may have implications for floodplain management and spillway designs. Further research and investigations are required to determine the extent of these potential impacts.

Conclusions

- Forest thinning in the northern jarrah forest water supply catchments clearly has the potential to significantly increase water yield while simultaneously benefiting timber production.
- Current best estimates of potential long term streamflow increases from fully thinned catchments are of the order of 11% of rainfall. For the maximum estimated area suitable for thinning in water supply catchments (about 1000 square kilometres), this translates to a total streamflow increase of 127 million cubic metres, which is 47% above current streamflow volumes.
- Of the 127 million cubic metres of increased streamflow, only 48 million cubic metres would be currently utilizable by the Metropolitan Water Supply System, due to various losses.
- Forest thinning is considerably more attractive in the high rainfall zone than the intermediate

rainfall zone, because of faster response, more water yield per unit area thinned, lower cost, and the absence of stream salinity risk. If only the high rainfall zone was thinned, 37 million cubic metres of the estimated 65 million cubic metres increased streamflow could be utilized by the Water Supply System.

- The cost of producing the estimated total utilizable yield from thinning in the high rainfall zone ranges from 1-5 cents per cubic metre, depending on the method of silvicultural treatment and utilization of thinned products. The cost compares favourably with the alternative of developing new sources at a minimum cost of 20 cents per cubic metre.
- Research currently underway to quantify areas suitable for thinning, streamflow increases, and potentially adverse environmental impacts should progress hand-in-hand with large-scale catchment operational thinning trials.

Recommendations

1. That an operational-scale forest thinning project be carried out in the high rainfall zone of the South Dandalup catchment with a view to testing the feasibility of silviculture for water production at a regional scale.

2. That potential streamflow increases resulting from silviculture for water production be determined more accurately by carrying out further detailed analyses of experimental catchment responses across a range of conditions, and by further development of modelling capability.

3. That a detailed regional inventory of forest resources be carried out to accurately define areas available and silvicultural treatments required for water production.

4. That a more sophisticated cost-benefit analysis be undertaken when more accurate estimates of water yield increases and areas suitable for treatment are available.

5. That research be continued on the potential effects of forest thinning on dieback spread and/or intensification and stream salinity, with the aim of developing techniques to minimise these impacts.

2. *Introduction*

Increasing water demand in the Perth-Bunbury region has traditionally been satisfied through the development of additional water resources. Since most of the more readily accessible, lowest cost water resources in the region are currently being utilized, further development of resources will be increasingly expensive. One option for increasing the capacity of the Perth Metropolitan Water Supply System is to make current water supply catchments more effective by increasing streamflow through forest density reduction.

Silvicultural methods to reduce forest density are well established in forestry practice world-wide. They are commonly used to enhance timber production but have not often been used to increase water yield. In Western Australia, silvicultural thinning of forests is carried out in the *Pinus pinaster* plantations in the Gnangara groundwater area and in the jarrah forest. These operations are, at present, mainly aimed at improving timber production.

In the jarrah forest, there is considerable potential for increasing silvicultural thinning to achieve both enhanced timber and water yields. This report reviews this potential from the water resources perspective. It describes silvicultural methods, provides quantitative estimates of potential streamflow increases, discusses uncertainties associated with thinning and details research in progress to support an increased programme of thinning for water production.

3. *Managing the Forest for Increased Water Production*

3.1 History of Forest Logging

The northern jarrah forest has been subject to logging activity for about 100 years and during this time it has nearly all been cut over at least once. Logging practice and intensity have varied greatly according to location, forest quality and the silvicultural practice of the day. As a result, the forest now consists of a mosaic of various ages and structures of mixed-age and even-age regeneration.

Prior to the creation of the Forests Department in 1918, timber cutting was not controlled. High quality areas were sought and subjected to heavy cutting or clearfelling. This has given rise to dense regrowth stands which today are of pole size, overstocked and slow-growing.

In the period from 1920 to 1940, a group selection silvicultural system was used. This involved virtual clearfelling in a patchwork pattern, the objective being to create good regeneration conditions on the cut-over patches and to retain uncut patches with better growth potential. Since 1940, the group-selection cut areas, and all other uncut or lightly cut forest, have been subjected to single tree selection cutting. This has given rise to mixed-aged stands which are usually also overstocked and slow-growing.

During the 1960s some of the even-aged pole stands were thinned to increase growth rates.

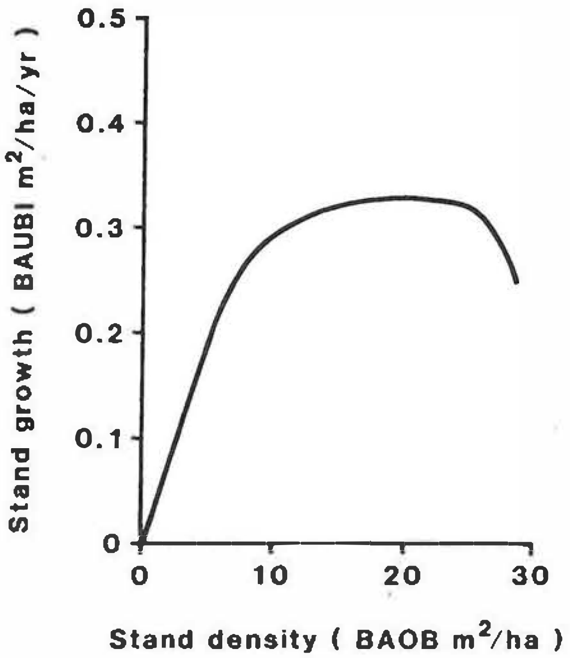


Figure 1
The stand density (BAOB: basal area over bark) - stand growth (BAUBI: basal area under bark increment) relationship for a regrowth jarrah pole stand

3.2 Silviculture for Wood Production

A major review of silvicultural practice was carried out in 1985. This review decided on a re-introduction of a group-selection cutting system. The main objective of this system is to regenerate or maintain even-aged groups amenable to thinning and adaptable to the present very mixed range of stand structures, ages and condition.

Three basic stand treatments were proposed :

(i) *Thinning:* a stand is amenable to thinning when sufficient crop trees are available for retention. Typically, regrowth stands have a tree basal area greater than 30 m²/ha. Figure 1 shows the relationship between stand growth rate and stand basal area. Maximum stand growth occurs in the basal area range 10-25 m²/ha. By thinning down to 10 m²/ha, the total growth rate of the stand is maintained while the growth rate of individual crop trees is more than doubled. Depending on average tree size and marketability, a basal area of 10-15 m²/ha is normally retained in thinning. Where slightly less than 10 m²/ha of suitable jarrah crop trees are available, the thinning treatment may still be applied but some marri and sheoak may be retained. However, these commercially less attractive species are not retained within four metres of a jarrah crop tree, the objective being to release the crop tree from immediately adjacent competition. This form of thinning is known as individual tree release.

Even-aged stands, with their uniform and abundant regeneration, usually will be suitable for direct thinning. Mixed-aged stands, with patchier regeneration, will often require treatments (ii) and (iii) before thinning can be applied. Stand structure therefore provides a rough guide to which treatment is applicable.

(ii) *Group felling and regeneration:* where too few crop trees are available but an adequate population of ground coppice is present, the group felling and regeneration treatment is applied. The overstorey is completely removed permitting the ground coppice to regenerate into an even-aged stand. When sufficiently well grown into the pole stage (about 20 years), this stand can be subject to thinning treatment (see (i)).

(iii) *Shelterwood treatment:* with too few crop trees and inadequate ground coppice, the overstorey is only partly removed, with enough being retained to aid new ground coppice to establish and develop. When a sufficient population is present the shelterwood is removed and the ground coppice regenerates into a new stand as for treatment (ii).

3.3 Silviculture for Water Production

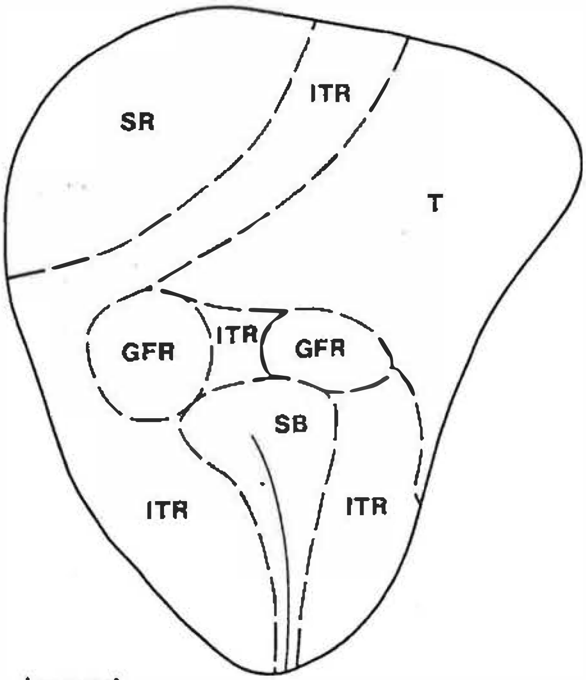
The major objective of silviculture for wood production, i.e. thinning to increase growth rate of selected trees, also reduces forest canopy cover and so increases streamflow. Thus the objectives of wood and water production are for the most part complementary. In considering the potential for integration of these two objectives into forest management, it is necessary to define the situations where they do not completely mesh. Five such areas exist :-

(a) A forest stand is dynamic and cannot be held at a fixed basal area. After a thinning treatment, the remaining stems with their enhanced growth rate will begin increasing in basal area. Thus to maintain individual stem growth rates at a high level and to maintain increased streamflow, regular re-thinning will be required. A greater frequency of re-thinning may be more desirable for the water production objective than for the wood production objective.

(b) The target basal area desirable for wood production alone is in the range 10-15 m^2/ha. For both wood and water production, a lower range might be appropriate, even though this would involve some loss of wood production potential.

(c) Where the group felling and shelterwood treatments (section 3.2(ii) and (iii)) are necessary, the stand must first pass through the regeneration stage before becoming suitable for thinning. The regeneration treatment will initially increase streamflow but this benefit will decline over the period up to the first thinning. Thinning too early will decrease wood production potential. A compromise between potential wood and water benefits must therefore be chosen at this stage.

(d) From the wood production perspective, the best returns will come from the existing high-quality, even-aged stands that are suitable for immediate thinning. These stands are often located in upper topographic positions. From the water production perspective, best returns will come from lower slopes on which poorer quality mixed-aged stands are more common. The initial regeneration treatment usually necessary in these stands makes their treatment economically unattractive for wood production alone, especially in comparison to immediately thinnable even-aged pole stands. However, with the dual objectives of wood and water production, more extensive treatment of a wide range of forest types could be justified.



Legend
SR - Shelterwood and regeneration
ITR - Individual tree release
T - Thinning
GFR - Group felling and regeneration
SB - Stream buffer (no treatment)

Figure 2
Schematic of silvicultural treatments applied to a catchment for water production

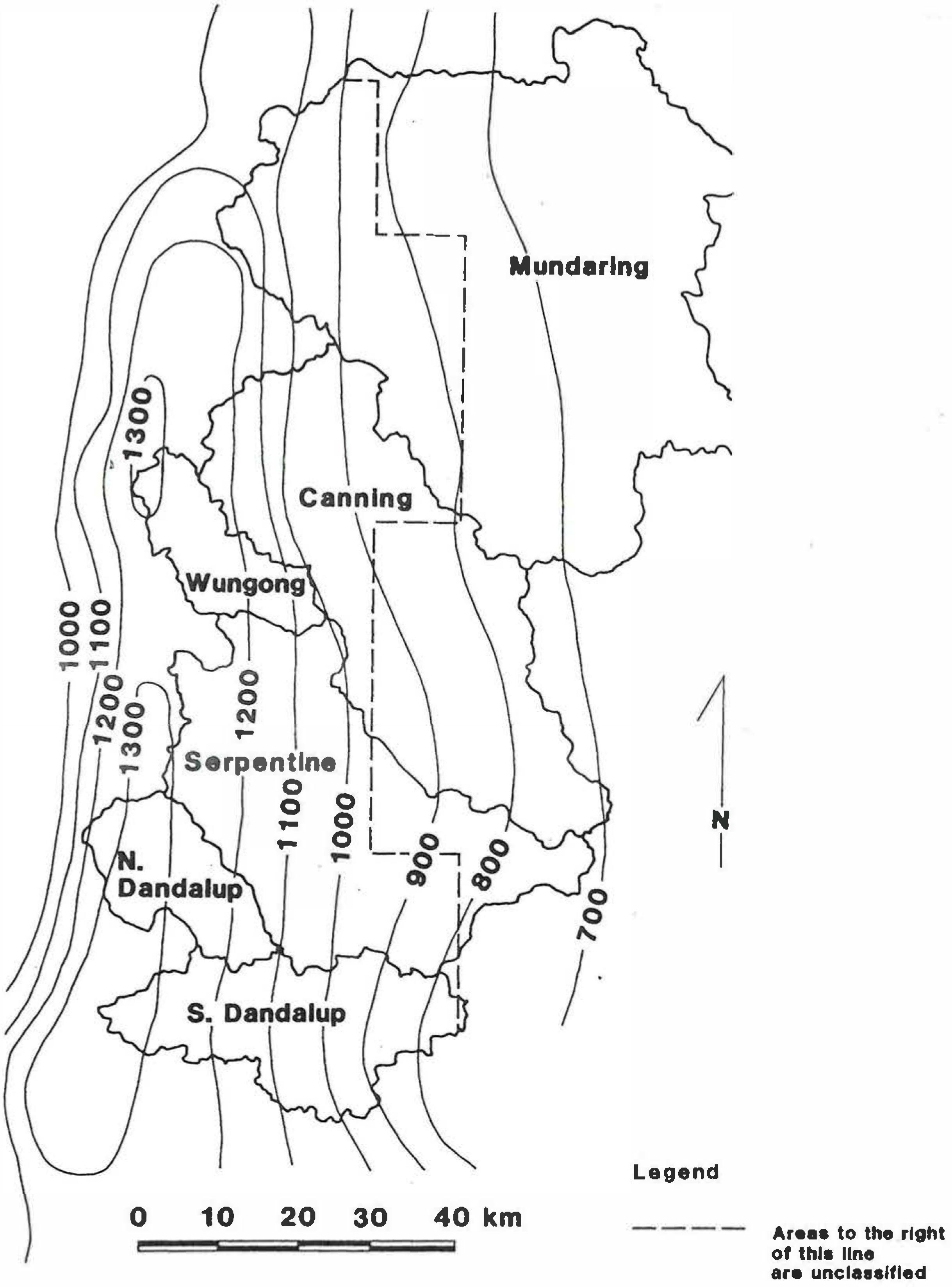


Figure 3
Water supply catchments, rainfall isohyets and forest classification demarcation for the northern jarrah forest

Table 1
Areas suitable for silvicultural treatment by stand structure, rainfall zone and catchment

	Even-age stands			Mixed-age stands			All stands			
	HRZ	IRZ	total	HRZ	IRZ	total	HRZ	IRZ	total	
Catchment	km²	km²	km²	km²	km²	km²	km²	km²	km²	%*
Mundaring	10	66	76	6	20	26	16	86	102	7
Canning	40	89	129	2	62	64	42	151	193	26
Wungong	50	1	51	18	2	20	68	3	71	54
Serpentine	79	104	183	49	91	140	128	195	323	50
N Dandalup	75	0	75	43	0	43	118	0	118	80
S Dandalup	60	60	120	35	50	85	95	110	205	66
Total	314	320	634	153	225	378	467	543	1010	

HRZ - High rainfall zone
IRZ - Intermediate rainfall zone
* - Percentage of total catchment area

(e) The individual tree release treatment retains some cover of species of little commercial value. Retention of these species results in lower potential for water yield benefit without a gain in wood production. Stands to which this treatment might be applied for wood production alone might be more appropriately totally thinned to a lower basal area for the alternative water production objective.

In silviculture for water production, a range of treatments would be implemented in any one catchment. This situation is depicted in a simple schematic form in Figure 2. In practice the situation may be more complex since factors such as dieback occurrence and hazard must be considered in the allocation of treatments.

3.4 Areas Available for Silvicultural Treatment

To determine what areas would be available for silviculture for the combined management of wood and water production, a survey of the northern jarrah forest was undertaken using the CALM Forest Management Inventory System (FMIS) data base. The area of each of the two stand structures (even-aged, mixed-aged) within the high and intermediate rainfall zones was defined for each of the six major water catchments (Figure 3). The data are presented in Table 1. A full description of this work is available in Hammond (1987) and Stoneman *et al.* (in prep).

The low rainfall zone (less than 900 mm/year annual rainfall) has been excluded from consideration for thinning because of the salinity risk. Other qualifications and uncertainties about the Table 1 data are discussed in section 5.2 and 5.3.

3.5 Management for Wood and Water Production

If a commitment is to be made to increasing water yield by silvicultural methods, this objective must be incorporated into the planning of forest operations. Silvicultural treatments are a part of integrated logging operations which include the simultaneous extraction of several different products (sawlogs, salvage logs, poles, posts, firewood and possibly residue for charcoal). These operations must be co-ordinated with dieback and fire management and with bauxite mining. Lead times of several years are involved in the detailed planning of these activities. A similar time would be required for full-scale adoption of treatments to meet a water production objective.

4. *Potential for Streamflow and Water Supply Yield Increases*

4.1 Effects of Forest Density Reductions on Streamflow in the Jarrah Forest

In a world-wide context, the hydrology of the jarrah forest is unusual in producing little streamflow from moderate rainfall. Streamflow from the northern jarrah forest catchments is, on average, only 9% of rainfall. Many studies of the effects of forest treatments on streamflow have been reported in the literature. A major review by Bosch and Hewlett (1982) suggested that for each 10% reduction in forest cover there has been an average increase in annual streamflow of 40 mm. The component of eucalypt forest included in this analysis was very limited and the results are not directly applicable.

Local studies of the effects of silviculture for water production have been initiated but it is too early for results to be conclusive. In the meantime, quantitative estimates of the effects of forest density reduction on water yield have been derived from: the measured effects of various forest treatments on research catchments; canopy cover - streamflow relationships; and model simulations. These estimates, and preliminary results from the forest thinning experiments, are discussed below.

4.1.1 Estimates from various forest treatments on experimental catchments

A number of experimental catchments (Figure 4) in the jarrah forest have been subject to forest treatments. These treatments include agricultural clearing, clearfelling and regeneration, and selection cutting. Their effects on streamflow are summarised in Table 2. Three main conclusions are evident:

(i) the greater the forest density reduction the greater the streamflow increase (other factors being similar);

(ii) higher streamflow increases occur in areas with higher long-term rainfall;

(iii) higher streamflow increases occur when permanent groundwater is at the ground surface within a catchment.

Most of the forest treatments shown in Table 2 would not be directly representative of silvicultural treatments for increased water yield. In the high rainfall zone, Lewin South catchment was considered to be the most representative, although the logging was somewhat more intensive than the proposed silviculture for water production. However, regeneration on this catchment was rapid and, combined with an increase in soil water storage, would have significantly decreased streamflow. Assuming that the more intensive logging was offset by regeneration and increased soil water storage, the appropriate estimate of streamflow increase for this catchment was taken to be the average increase of the first three full calendar years following treatment.

In the intermediate rainfall zone, April Road North catchment was considered to be the most representative of silviculture for water production. In this case, the estimate is likely to be high because the catchment was clearfelled, except for the stream buffer (10% of the area). Again the appropriate estimate of streamflow increase was taken as the first three full calendar years following treatment.

It should be emphasised that neither of the above two catchment treatments are particularly representative of thinning. However, the values of streamflow increases measured for these two catchments are considered to be of the correct order when the wider evidence of Table 2 is taken into account. In particular it should be noted that permanent reductions in vegetation density result in on-going increases in streamflow, as evidenced by Wights catchment, where streamflow has increased consistently since clearing, reaching some 30% of rainfall in seven years (Williamson *et al.*, in press). In the forest thinning process, regeneration is eliminated but the leaf area of the crop trees increase. This will partially counteract ongoing streamflow increases, at least until the second thinning occurs.

4.1.2 Estimates from canopy cover - streamflow relationships

The relationship between canopy cover and streamflow for six high rainfall zone catchments is shown in Figure 5a. The large differences in canopy cover between these catchments are mainly attributed to dieback disease. The effect of reduced canopy on streamflow is both clear and dramatic. A reduction of cover from 50% to 20% (equivalent to a basal area reduction of 38 m^2/ha to 11 m^2/ha) corresponds to a streamflow increase of 18% of rainfall. This result should be treated with some caution because dieback occurs preferentially in valley bottoms and on upslope areas associated with higher shallow throughflow.

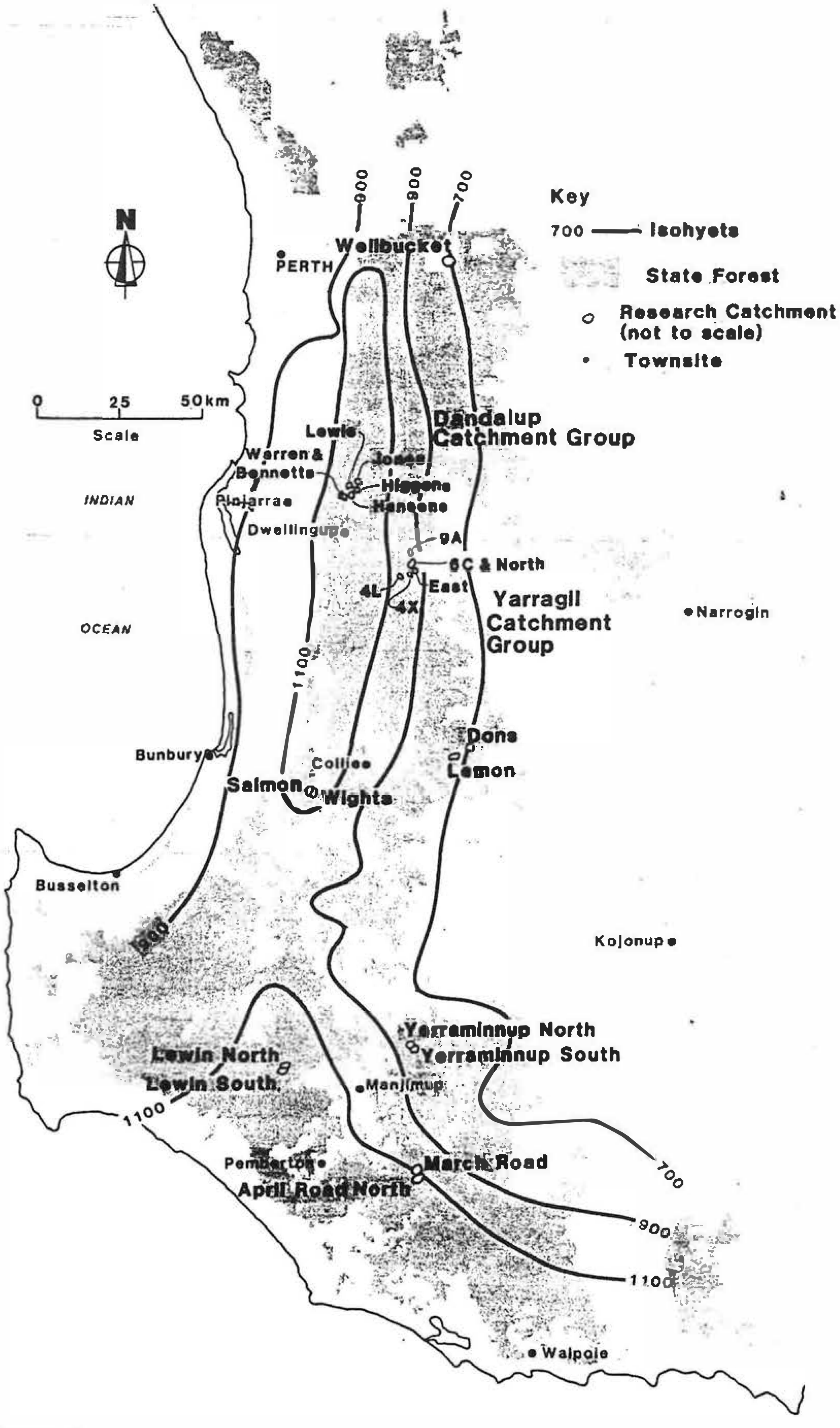


Figure 4
Research Catchments in the Jarrah Forest

Table 2
Summary of streamflow increases of research catchments following forest reduction

Catchment*	Long term rainfall mm	Treatment	Forest reduction	Post-treatment monitoring	Average annual streamflow increase since treatment mm	%rain	% flow	Max. annual streamflow increase mm	%rain	Groundwater at surface
Wights	1200	Agricultural development	PCF 100-0	1976-86	239	23.9	272	359	32.5	Yes
Lemon	800	Agricultural development	PCF 100-46	1976-83	17	2.1	279	38	4.8	No
Dons	800	Agricultural block, strip & parkland clearing	PCF 100-62	1976-83	11	1.4	286	38	4.8	No
March Road	1070	Clearfelling & regeneration	CC 65-0	1982-85	121	11.3	147	196	18.3	Yes
April Road North	1070	Clearfelling leaving 100m buffers & regeneration	CC 65-0 buffer 10% of area	1982-85	104	9.7	167	155	14.5	Yes
Lewin South	1220	Selection cut & regeneration	CC 70-11 BA 44-7	1982-85	116	9.5	81	178	14.6	Yes
Yerraminnup South	850	Logging leaving 50 m buffer & regeneration	CC 70-10 buffer 12% of area BA 44-5	1982-85	20	2.3	83	38	4.5	No
Wellbucket	700	Selection cut & regeneration	CC 38-20 BA 16-11	1977-81	2	0.3	128	3	0.4	No
Yarragil 4L	1120	Thinning	CC 55-22 BA 35-11 LAI 1.9-.6	1983-85	17	1.9	293	31	3.1	No
Hansen	1300	Thinning	BA 35-7	1986	40	3.8	83	40	3.8	Yes

CC = crown cover (%), BA = basal area (m^2/ha), PCF = percentage of catchment forested, LAI = leaf area index
* see Figure 4

These areas are likely to contribute a greater proportion of the catchment streamflow. Predictions of streamflow increase based on these data would therefore be greater than the actual increases which would result from silvicultural treatment.

The canopy cover-streamflow relationship for a selected group of catchments in the intermediate rainfall zone is shown in Figure 5b. In this case, a reduction in canopy cover from 50% to 20% is associated with a streamflow increase of 11.5% of rainfall. The areas of these catchments affected by dieback are much smaller than in the high rainfall zone and the result reflects more the natural variation in stand density.

4.1.3 Estimates from model simulations

The Darling Range Catchment Model (DRCM) (Hopkins, 1984, Mauger 1986) has been used to simulate the effects of forest thinning in the Canning catchment (Hammond, 1987). The model was calibrated using rainfall and streamflow data for the period 1912-1983. In the simulation model, forest thinning was applied to only the classified portion of the catchment (Figure 3). In this simulated catchment, 64% or 14700 ha of forest was considered suitable for thinning for water production. Two thinning scenarios were modelled for the period 1911-1984. They involved thinning at approximately 30-year intervals and catered to some extent for longer term periodic fluctuations in forest density. The average streamflow increase

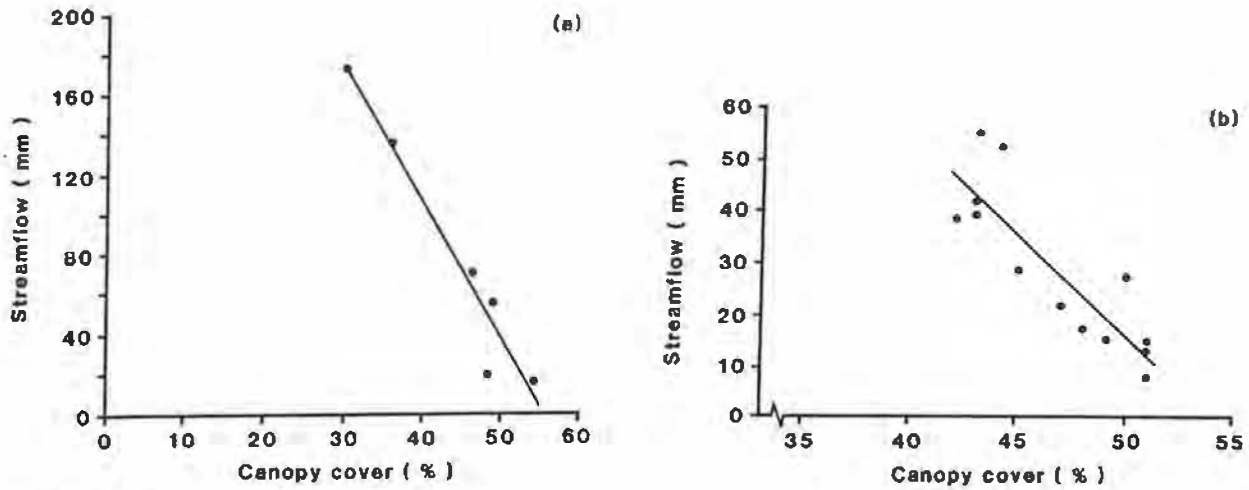


Figure 5
Relationship between canopy cover (%) and streamflow (mm) in the northern jarrah forest for (a) 6 catchments in the high rainfall zone and (b) 13 catchments with similar physical characteristics in the intermediate rainfall zone

for the two thinning scenarios was 11.5% of rainfall. The simulated catchment covered a rainfall range from slightly above 800 mm/year to greater than 1200 mm/year, and so the streamflow increase was assumed to be applicable to both the high and intermediate rainfall zones.

4.1.4 Early indications from thinning experiments

To date two experimental catchments have been thinned to assess the effects on streamflow.

Yarragil 4L catchment, located near the western edge of the intermediate rainfall zone (Figure 4), was thinned in 1983 from a basal area of 35 m^2/ha to 11 m^2/ha. Little streamflow increase (3 mm) occurred in the first year following thinning, a response Stoneman (1986) attributed to increases in soil water storage. In the second year following thinning, there was a significant increase in streamflow of 31 mm. Additionally, groundwater levels in midslope and valley bottom bores have been rising at a rate of about 1 metre per year, and so on-going increases in streamflow are expected.

The effect of thinning Yarragil 4L catchment was simulated with the Darling Range Catchment Model. The model predicted only small increases in the first four years, but substantial increases after four or five years. Maximum streamflow increase occurred in the simulation at five years, after which it gradually declined as leaf area increased. Over the period five to ten years following clearing, the predicted streamflow increases were 125 mm/year (11.2% of rainfall).

Hansens catchment (Figure 4) (1300 mm/year average annual rainfall) was thinned from 35 m^2/ha to 7 m^2/ha in 1985. Data are available for only one year following thinning, but these data indicate a considerably larger streamflow increase (40 mm) than the first year of Yarragil 4L, despite very low 1986 rainfall. The larger increase is attributed mainly to the fact that groundwater is already at the ground surface in the valley bottom of this catchment.

4.1.5 Summary of estimated changes in streamflow

The three different methods of estimating streamflow increase are summarised in Table 3. Although each estimate has relatively low reliability, there is some consistency between estimates. The mean estimated streamflow increases are also consistent with Bosch and Hewlett (1982) who predicted an average increase of 120 mm for a 30% change in forest cover.

The estimated streamflow increases as a percentage of rainfall (Table 3) are similar for both the high and intermediate rainfall zones. Absolute streamflow increases are greater at higher mean annual rainfall, a relationship also noted by Bosch and Hewlett (1982).

In the intermediate rainfall zone, significant streamflow increases are likely to be delayed due to the time taken for groundwater to rise and form saturated source areas in valley bottoms.

Table 3
Summary of estimates of streamflow increases resulting from forest thinning

Method of obtaining estimate	Streamflow increase in high rainfall zone rainfall zone (1200 mm/yr)		Streamflow increase in intermediate rainfall zone (1000 mm/yr)	
	mm	% rainfall	mm	% rainfall
Forest cover relationships	218	18.2	115	11.5
Modelling	138	11.5	115	11.5
mean	165	13.7	116	11.6
minimum	138	11.5	115	11.5

4.2 Estimated Streamflow Increases in Water Supply Catchments

Individual catchment streamflow increases have been estimated by multiplying the area of the catchment suitable for silviculture for water production by the lowest estimated streamflow increase for each rainfall zone (Table 4). The estimated catchment streamflow increases range from 25% to 81% of long-term mean annual flows. The estimated total streamflow increase amounts to 127 million cubic metres or 47% of the long-term mean annual flow. This amount is approximately equally divided between the high rainfall zone and the intermediate rainfall zone.

4.3 Estimated Reservoir Yield Increases from Water Supply Catchments

The ability to harness increased streamflow is limited by loss through spillage, evaporation, the mechanism and capacity of reservoir withdrawal and other factors. One of the main factors determining the magnitude of the loss is the reservoir storage/long term annual inflow ratio (Table 5). On this basis, the South Dandalup dam has the greatest capacity to accept additional streamflow and the Canning Dam the least.

The potential increase in reservoir yield has been determined by running the Metropolitan Water Supply System computer simulation model with the projected increased streamflows (G. Mauger pers. comm.). A variety of options have been simulated and are summarised in Table 6. With the

Table 4
Estimated streamflow increases for individual water supply catchments

Catchment	Total area (km^2)	HRZ area to be treated (km^2)	IRZ area to be treated (km^2)	HRZ streamflow increase (mm)	HRZ streamflow increase (10^6m^3)	IRZ streamflow increase (mm)	IRZ streamflow increase (10^6m^3)	Current ann. av. streamflow (1911-1986) (mm)	Current ann. av. streamflow (1911-1986) (10^6m^3)	Estimated streamflow increase (mm)	Estimated streamflow increase (10^6m^3)	Estimated streamflow increase (%)
Mundaring	1456	16	86	1.5	2.2	6.8	9.9	33.1	48.2	8.3	12.1	25
Canning	732	42	151	7.9	5.8	23.7	17.3	80.5	58.9	31.6	23.1	39
Wungong	132	68	3	71.1	9.4	2.6	0.3	203.8	26.9	73.7	9.7	36
Serpentine	647	128	195	27.3	17.7	34.7	22.5	115.0	74.4	62.0	40.1	54
N. Dandalup	148	118	0	110.0	16.3	0	0	202.0	29.9	110.0	16.3	54
S. Dandalup	310	95	110	42.3	13.1	40.8	12.6	102.3	31.7	83.1	25.8	81
Total		467	545		64.5		62.6		270.0		127.1	47

HRZ : high rainfall zone
IRZ : intermediate rainfall zone

current limitations on combined trunk main capacity, the potential yield increase of the water supply system resulting from a full thinning programme in the high and intermediate rainfall zones is 37% of the estimated streamflow increase. This proportion could be increased to 53% if the trunk main capacities were upgraded. If only the high rainfall portion of the area available for thinning was treated, then 57% of the estimated streamflow increase would be utilized. Moreover, with the current trunk main capacity, this represents 77% of the increased yield from both high and intermediate rainfall zones.

Table 5
Reservoir storage/inflow ratios

	Mundaring	Canning	Wungong	Serpentine	North Dandalup*	South Dandalup
Storage /inflow ratio	1.6	1.5	2.2	2.5	2.5	5.0

* proposed dam

This result is significant because the potential for adverse environmental impact is greater in the intermediate rainfall zone.

Thinning of the South Dandalup catchment alone has been included in Table 6 because this catchment is considered suitable for a large-scale trial thinning project. With the current trunk main capacity, some 13.6 million cubic metres or 53% of the estimated streamflow increase is potentially available.

Table 6
Simulated increases of the Water Supply System* for a range of options

Option	Simulated increase in system water supply: With current trunk mains 10^6 m^3	%	With upgraded trunk mains 10^6 m^3	%
Full estimated streamflow increase (127.1 million m^3)	47.6	37	64.0	53
Estimated streamflow increase from HRZ only (64.5 million m^3)	36.6	57	39.6	62
Estimated streamflow increase from S. Dandalup only (25.8 million m^3)	13.6	53	16.2	63

* simulations assume construction of North Dandalup dam completed (1993)

4.4 Estimated Costs of Water Production by Silviculture

The total forest area in the high and intermediate rainfall zones suitable for silviculture for water production is estimated at 1010 square kilometres (Table 1). The cost of silvicultural treatment has been estimated by Stoneman *et al.* (in prep.) to range from $1100 to $3700 per square kilometre averaged over 15 years (depending on the type of treatment carried out). On this basis, the cost of adding the estimated 48 million cubic metres to the Metropolitan Water Supply would range from 2.3 to 7.9 cents per cubic metre. If only the high rainfall zone was treated, the cost of producing the estimated yield increase of 37 million cubic metres would range from 1.4 - 4.7 cents per cubic metre. Both of these costs compare favourably with the development of a new dam, the cheapest of which would provide water at 20 cents per cubic metre (Mauger, 1987).

5. *Implications and Uncertainties*

5.1 Interaction with Jarrah Dieback

It is well established that *Phytophthora cinnamomi*, the causal agent of jarrah dieback, is favoured by the co-incidence of warm and moist soil conditions (Shea, 1975). This is reflected in the concentration of disease in lowland sites in the northern jarrah forest where high soil moisture levels persist into the warmer summer months. The disease may also have a major impact on the forest in areas high in the landscape where it is associated with soil conditions which result in impeded drainage and lateral water flow (Shea *et al.*, 1983; Kinal, 1986).

It also appears that the fungus is sensitive to the water status of the host. Tippett *et al.* (1987) observed that lesion growth rate in jarrah was positively correlated with tree water status.

Since a forest thinning treatment may increase both site and host water status, it may also affect disease impact. However, wide experience with thinning and logging operations over many years has shown little indication of this effect. This suggests that the numerous other site and host factors which determine disease occurrence override the water status factor, and that risk of adverse consequences from thinning is small.

Current thinning operations have been authorized under existing CALM dieback policy (Forests Dept., 1982). This requires an analysis of risks, impacts and consequences of disease for each operational area. The analysis specifies the appropriate hygiene and hazard reduction techniques for each area.

Silviculture for water production could be authorized within these existing policy constraints. It remains desirable to further improve knowledge of disease processes and of disease management practices.

5.2 Stream Salinity

Silviculture for water production would most likely result in higher groundwater levels in valley bottoms in all areas treated. There is moderate potential in the intermediate rainfall zone and high potential in the low rainfall zone for this to cause an undesirable increase in stream salinity by mobilising salt stored in the soil profile. The extent to which this happens would depend on:

(i) whether groundwater would rise to the ground surface under particular silvicultural treatments;

(ii) the relative amount and salinity of groundwater, shallow throughflow and overland flow contributing to streamflow;

(iii) whether the resultant stream salinity significantly affects the regional water resources.

The effects of forest thinning on stream salinity, particularly in the intermediate rainfall zone, require further research. It is unlikely that silviculture for water production would be proposed for the low rainfall zone because of the limited benefits in streamflow increase obtainable.

5.3 Areas Suitable for Water Production

5.3.1 Detailed forest inventory

The estimates of areas available and the classification into even and mixed-aged stands to infer appropriate silvicultural treatment, as presented in Table 1, are based on crude, regional-scale data, and simplifying assumptions concerning treatments. A systematic, local-scale, ground survey-based inventory is required. It should focus on the following factors:-

(i) potentially treatable area;

(ii) structure, density, dieback occurrence and hazard, crop tree and ground coppice stocking;

(iii) topographic distribution of areas and types;

(iv) rainfall and catchment.

Factors listed in (ii) will show considerable local variation and data are essential to determine the appropriate silvicultural treatment. For example, fire damage may mean that an even-aged stand has insufficient crop trees for direct thinning and must first go through the felling and regeneration sequence more commonly applicable to mixed-aged stands.

Factor (iii) is important because of the likely bias of even-aged, immediately thinnable areas to upper topographic positions and of mixed-aged stands, requiring the regeneration step, to low positions. This may have important water yield consequences since streamflow generation from the upper topographic positions is limited. Also there is considerable local variation in the two types. For example, even-aged stands in the sub-catchments of the Yarragil catchment occupy anything from 10% to 80% of the area.

5.3.2 Interaction with bauxite mining

Significant forest areas suitable for thinning will overlap with bauxite mining. As a result, it is necessary to jointly plan forest silviculture and mining to avoid premature mining of areas which have been subject to costly silvicultural treatment.

Current minesite rehabilitation methods aim to regenerate a stable, productive forest ecosystem. This is achieved by the establishment of a dense, diverse and vigorous plant community. There are many benefits in this practice, but one disadvantage could be an eventual reduction in streamflow. It could be argued that rehabilitation offers the potential to design a system which both physically (in drainage systems) and biologically (low water-using species) favours higher streamflow. This latter option has not been developed because it is possible to have both a fully productive forest ecosystem and a desirable level of water production by imposing a thinning treatment to the rehabilitated areas at age 10-20 years. In this respect, rehabilitation practice is comparable to the regeneration step necessary in the silviculture of forest with insufficient crop trees.

5.3.3 Ecological Impacts

In terms of ecological impacts the proposed water production silviculture would differ little from long established wood production silviculture. Both mimic natural processes, such as competition and high intensity fire, which would otherwise operate to reduce forest stocking. Virgin jarrah forest is characterised by a 'parkland' structure. Thinning would hasten the achievement of such a natural structure but possibly with reduced development of some of the specialised habitat features of mature forest, such as tree hollows. For this reason any extensive application of silvicultural thinning would retain a population of mature trees in each locality.

5.4 Reliable Estimates of Streamflow Increases

The estimates of likely streamflow increases resulting from forest thinning were derived indirectly. Considerably more research is required to better quantify potential streamflow increases across the region. This will ultimately need to take account of the problems relating to the size and distribution of areas suitable for thinning.

5.5 Implications for Streamflow Distribution, Floodplain Management and Spillway Design

A high proportion of the streamflow in jarrah forest catchments is generated from shallow throughflow (Stokes and Loh, 1982). Forest thinning is likely to increase the extent of groundwater saturated areas which will increase overland flow, shallow throughflow and groundwater contributions to streamflow. Forest thinning would also increase streamflow in dry years. This would reduce annual variability in streamflow volumes and contribute to decreasing the probability of water restrictions in the Metropolitan Water Supply System.

Peak flows, however, could increase significantly as a result of increased saturated source areas and other fast stormflow components. In a study of the impact of bauxite mining in the jarrah forest (Steering Committee for Research on Land Use and Water Supply, 1984), catchment streamflow was found to increase by 20-30%, while peak flows increased 2-3 times. Intensive selection cutting and clearfelling and regeneration treatments on four Woodchip experimental catchments in the Southern Forests resulted in maximum annual peak-flow increases ranging from 3.3 to 5.3 times.

The significant potential increases in peak flows suggested above would have some impact on floodplain management. However, in major flood events it is anticipated that peak flows from treated catchments will exceed those from undisturbed forest by a significantly smaller amount. Also the major source of flood risk in the Perth-Bunbury region is runoff from agricultural land east of the jarrah forest.

Increases in peak flows would also have an impact on spillway design. Spillways of the northern jarrah forest water supply catchments are currently under review and some upgrading will be required. Forest thinning would increase the need to upgrade those spillways with inadequate capacity.

6. Research Programme

During the middle to late 1970s a research programme was commenced to investigate the water resource impacts of forest management strategies aimed at increasing both timber and water yields. At that time, the risk of stream salinity increase was a particular concern in the intermediate rainfall zone. More recently, the potential spread and/ or intensification of dieback disease has gained prominence.

As part of the research programme, catchments were selected to cover the range of forest densities and forest structures across the high and intermediate rainfall zones. The locations of these catchments are shown in Figure 4 and some of their characteristics are given in Table 7.

The treatments of the experimental catchments have been delayed because of the significantly drier than average sequence of years encountered in the early calibration years. The forest treatment programme for the high rainfall zone catchments was also modified in 1986 due to the re-direction of bauxite mining through the region of the experimental catchments. To date, treatments have been carried out on three of the experimental catchments. These treatments, together with the proposed treatments for the other catchments, are summarised in Table 8.

Various other activities have been initiated, or are being planned, to augment these catchment experiments and help resolve some of the uncertainties of a forest thinning programme. These activities include plot thinning trials, dieback studies, regional inventories and further catchment-scale modelling.

Plot thinning trials are designed to evaluate leaf area recovery, changes in leaf water use and changes in soil water content resulting from thinning.

Management of dieback disease is based on prevention of the spread of the fungus (i.e. hygiene) and manipulation of site and host conditions to disfavour the fungus (i.e. hazard reduction). Developing hazard reduction measures has required intensive research on the site and host characteristics and processes giving rise to disease. Silviculture for water production may alter site and host characteristics in favour of the fungus. Further research specific to this problem is therefore warranted. In particular, better definition of low hazard sites and other

Table 7
Some relevant characteristics of forest management research catchments

Catchment[1]	Area (ha)	Rainfall[2] (mm)	Streamflow[3] (mm)	Stream[3] salinity (mg/L)	Groundwater[3] salinity (mg/L)	Area of dieback (%)	Crown cover (%)
Warren	87	1325	169	123	-	60	37
Bennetts	88	1330	207	93	-	60	40
Hansens	73	1340	76	115	-	27	42
Higgins	60	1300	30	124	-	0	45
Lewis	201	1350	74	112	-	26	40
Jones	69	1300	10	143	-	6	50
Yarragil 4L	126	1120	10	182	205	-	60
Yarragil 4X	258	1070	16	447	1052	4	56
Yarragil 9A	580	1030	4	357	765	-	-
Yarragil 6C	458	1050	9	382	1064	-	-

1 See Figure 4
2 Estimated long term values
3 Average of values measured over limited period

avoidable risk factors is necessary to guide operations.

The establishment of a more detailed inventory of forest density and structure is a high priority. Such an inventory will enable a more accurate analysis of areas suitable for silviculture for water production, and will provide input data for regional modelling. The regional catchment model developed by the Water Authority (DRCM) requires further development to better predict changes in water yield and stream salinity as a result of changes in forest density.

Table 8
Summary of treatments and proposed treatments for forest management research catchments

Catchment	Treatment or proposed treatment
Warren	Most of the dieback degraded area was intensively rehabilitated in 1984/85. However mining of this catchment is now to take place in the period 1988-92. It is planned to intensively rehabilitate the mined area with maximum possible vegetation density to evaluate the effect of this treatment on streamflow.
Bennett	Mining is to be carried out in the period 1988-92. This is to be followed by 'standard' rehabilitation of pits and diseased areas.
Hansen	A uniform forest thinning treatment, reducing forest density to 7 m^2/ha basal area, was carried out in 1985/86. This aimed to test streamflow and dieback disease responses. Mining, due in the vicinity of this catchment in 1995-98, should be excluded, although a severe dieback disease reaction to thinning would be grounds for review.
Higgins	A forest thinning treatment is proposed in 1987/88 or a mining treatment in 1992.
Lewis	This catchment will serve as a control catchment until 1996 when it will be mined. It is currently proposed to have the standard mining and forest management treatment of the day.
Jones	Proposed to have a forest thinning treatment in 1988/89. This catchment will be required to test on-going forest management and should be permanently excluded from mining.
Yarragil 4L	Forest thinning was carried out in 1983, reducing the forest density to 11 m^2/ha. The main objectives are to determine the impact on water yield and stream salinity.
Yarragil 4X	A forest treatment is to be carried out in the next four years. The type of treatment is as yet unspecified.
Yarragil 9A	As above.
Yarragil 6C	Currently proposed to remain as a control for the above Yarragil catchments.

7. *Conclusions*

- Silvicultural treatments of Metropolitan water supply catchments have the clear potential to significantly increase catchment water yield while simultaneously benefiting timber production.
- The area of water supply catchments available for silvicultural treatment is estimated to be 1000 square kilometres. Of this, 460 square kilometres lie in the high rainfall zone and 540 square kilometres lie in the intermediate rainfall zone. These values are based on limited forest information and may represent an over-estimation of the true areas.
- Three indirect estimates of streamflow increase following silvicultural treatment for water production were derived and ranged from 11.5 - 18.2% of rainfall (approximately 140 - 220 mm of streamflow) for the high rainfall zone, and from 11.5 - 11.9% of rainfall (approximately 115 - 120 mm of streamflow) for the intermediate rainfall zone. Each estimate individually was considered to have relatively low reliability as a predictor of streamflow increase following silviculture for water production.
- The total streamflow increase was calculated at 127 million cubic metres, or a 47% increase in the current average streamflow. This calculation was based on the total estimated area suitable for treatment (1010 km^2) and the lowest estimated streamflow increase (11.5% of rainfall) assumed to apply to only the treated area. The total water supply catchment yield increase was approximately equally divided between the high rainfall zone and the intermediate rainfall zone.
- Of the 127 million cubic metres increased streamflow, only 48 million cubic metres would be utilized by the Metropolitan Water Supply System because of spillage, evaporation, trunk main capacity and other factors. If only the high rainfall zone was treated, 37 million cubic metres of the 65 million cubic metres estimated streamflow increase would be utilized by the water supply system.
- The cost of producing the estimated total utilizable yield would range from 2.3 to 7.9 cents per cubic metre, depending on the method of silvicultural treatment and utilization of products from thinning. For the estimated increased water yield from the high rainfall zone only, the cost range would be from 1.4 to 4.7 cents per cubic metre. In both cases the cost compares favourably with the alternative of developing new sources at a minimum cost of 20 cents per cubic metre.
- The proposition of silviculture for water production is considerably more attractive in the high rainfall zone than the intermediate rainfall zone because of faster response, more water yield per unit area thinned, lower cost, and smaller potential environmental impacts.
- An array of uncertainties require clarification to facilitate development of the thinning option, including better definition of yield increase and area available, engineering aspects of storage design and management, and complications with dieback and stream salinity.

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Appendix

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Glossary

basal area	The cross-sectional area of a tree usually measured at breast height (1.3 m above ground) including bark. When applied to a forest, the sum of the basal areas of all stems, usually expressed as the total basal area per unit of ground area.
clearfelling	The felling of all trees, including unusable trees, carried out in a given area to achieve uniform, even-aged regeneration.
crop tree	A tree meeting height, form and crown structure specifications sufficient for retention in a thinning operation.
cut-over area	An area that has been logged.
dieback disease	In the jarrah forest, the disease caused by the pathogenic fungus *Phytophthora cinnamomi*, a common symptom of which is progressive dying back within the tree crown.
dieback hazard	The potential severity of dieback disease at a site, rated low, moderate or high.
dieback hygiene	Any measure taken to reduce man-aided spread of the dieback fungus.
evapotranspiration	The loss of moisture from the terrain by direct evaporation plus transpiration from vegetation.
even-aged	Applied to a stand in which relatively small age differences exist between individual trees.
ground coppice	The final stage in the lignotuberous phase of jarrah seedling development. Jarrah and many other eucalypts pass from a seedling into a lignotuberous seedling where a subsurface root stock is formed from which new growth can sprout if the aerial shoots are damaged by fire, drought or grazing.
groundwater flow	The flow of water in saturated aquifers.
group selection system	A silvicultural system in which groups (i.e. small areas about four times tree height in diameter) of trees are felled to permit even-aged regeneration.
individual crop release	The removal of competing trees within close proximity to selected crop trees, usually four metres radius, undertaken where too few crop trees are available to justify full thinning.
logging	Felling and hauling logs.
mixed-age	A stand containing trees of mixed ages usually including mature old growth and regrowth after selection cutting.

overland flow	That part of rainfall which fails to infiltrate the mineral soil surface at any point as it flows over the land surface to channels.
overstorey	The upper layer of vegetation in a forest formed by the crowns of the dominant trees.
pole stand	An even-aged stand of regrowth trees in the pole stage, usually 15-45 cm in diameter and more than 20 metres in height, and 20-50 years old.
regeneration	The process of forest renewal, or the plants resulting from this process.
regrowth	Regeneration at the sapling or pole stage of growth.
salinity	The concentration of dissolved salts in water.
sawlog	A log of suitable size and grade to produce sawn timber.
selection cutting	A silvicultural system in which selected trees are felled in order to maintain the stand in an uneven-aged condition.
shelterwood method	The retention of some mature trees to provide seed source and cover to facilitate seedling establishment and regrowth
silviculture	The art and science of establishment and tending of forest.
stand	An aggregation of trees or other growth sufficiently uniform in composition, age, arrangement and condition as to be distinguished from adjacent forest.
stand density	The stocking or number of trees in a stand per unit area.
stand structure	The framework of stems and crowns of different species and age. Varies according to site, species present (both under and overstorey) and cutting history which determines the stage of development of the regrowth.
stream buffer	An area of undisturbed vegetation adjacent to the stream.
throughflow	Downslope flow of water occurring physically within the soil profile, under both saturated and unsaturated conditions.
saturated source area	Saturated area of a catchment contributing to storm runoff.
water table	The surface of an unconfined groundwater body at which the pressure is atmospheric.
water yield	The quantity of water extracted from a reservoir for water supply.