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Silviculture for Water Production in Jarrah Forest of Western Australia: an Evaluation

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ABSTRACT

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The development of new surface water sources to meet the growing demand of the Perth Metropolitan Area is becoming increasingly costly because most of the readily available surface water sources in the jarrah (*Eucalyptus marginata* Don ex Sm) forest have been utilised. There is also growing concern that the Greenhouse Effect will significantly reduce streamflow from existing water supply catchments over the next 50 years. One method of increasing streamflow is to reduce the density of forest on the catchment areas.

Within the major Perth Metropolitan Water Supply catchments there are an estimated 1000 km^2 of State forest suitable for thinning. The lowest of four indirect estimates of streamflow increase due to thinning indicates that reservoir inflows could be augmented by 47% or 127 million m^3 $year^{-1}$, of which 48 million m^3 $year^{-1}$ could be harnessed by the present water supply system.

INTRODUCTION

Most of Western Australia is arid or semi-arid. Only 6% of the State is forested. Streamflow from this forested area comprises 79% of the public supply to the south-west region (Anonymous, 1984). The population of Western Australia is 1.3 million, of whom 90% live in the south-west, with over one million resident in the city of Perth. The rate of increase of water usage of Perth's public water supply since 1978 has been 6% $year^{-1}$ of current water use (calculated from Mauger, 1987, fig. 2). This demand necessitates the construction of new dams in the jarrah (*Eucalyptus marginata* Don ex Sm) forest, located at greater distances than existing supplies. These new developments will provide water at the cost of A$0.19–0.30 m^{-3}. This compared to A$0.11 m^{-3} for existing pipeheads and dams (Mauger, 1987).

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Concern is also growing that the Greenhouse Effect may result in significantly reduced rainfall and streamflow in south-west Western Australia (Sadler et al., 1988). Predictions indicate a decline in rainfall by as much as 20% by 2040. Use of a simple statistical relationship between historical rainfall and streamflow indicates that streamflow in the region could decline some 45% as a result of such a rainfall decrease (Sadler et al., 1988).

One option for increasing streamflow is to reduce forest density in the water supply catchments (Fig. 1). These catchments currently account for about 67% of Perth's public water supply. Streamflow from the northern jarrah forest catchments is, on average, only 9% of rainfall, the remaining rainfall evaporating back to the atmosphere. A substantial reduction in forest density should reduce transpiration and interception, and hence increase streamflow.

Most of the northern jarrah forest, an area of 10 500 km^2, has been cut-over since European settlement of the State. The forest is now composed of a variety of stand structures, much of which is suitable for intensive management for water and wood production (Shea et al., 1975, 1978).

Silviculture for water production would involve the thinning of pole stands and the conversion of other stand structures to a form suitable for long-term intensive management. The dense regrowth pole stands, resulting from heavy cutting earlier this century, are slow-growing because of intense competition and a slow process of self-thinning (Stoneman et al., 1988). Moreover, there is a substantial difference in streamflow between densely-stocked and lightly-stocked catchments (Schofield et al., 1988). Thinning of dense regrowth stands is thus likely to significantly benefit both water and timber production.

Silviculture for water production is not a new idea. Many authors have discussed the potential to increase streamflows in large water supply catchments by silvicultural treatment. Dortignac (1967) described the potential in the U.S.A. Ffolliott and Thorud (1978), Hibbert (1979), Kattleman et al. (1983) and Bowes et al. (1984) concentrated on the south-west of the U.S.A. where water supply is limited. Harr (1983) discussed the potential in western Washington and western Oregon, and Douglass (1983) in the eastern United States. Alexander (1986a,b,c) recommended silvicultural systems for water production for three of the major forest types in the Rocky Mountains. Ronan et al. (1982) discussed silvicultural options and their likely effects on water and wood production from the Melbourne and Metropolitan Board of Works catchments.

In Western Australia the importance of silvicultural management of the forest on water values was recognised as early as the 1920s. The objective of the Forests Department 1921 Mundaring Working Plan was to maintain a well-regulated supply of pure water in the catchment. Intensive research on the effects of silviculture on water values in the jarrah forest started in the early 1970s (Shea et al., 1975, 1978). Thinning of *Pinus pinaster* Ait. plantations

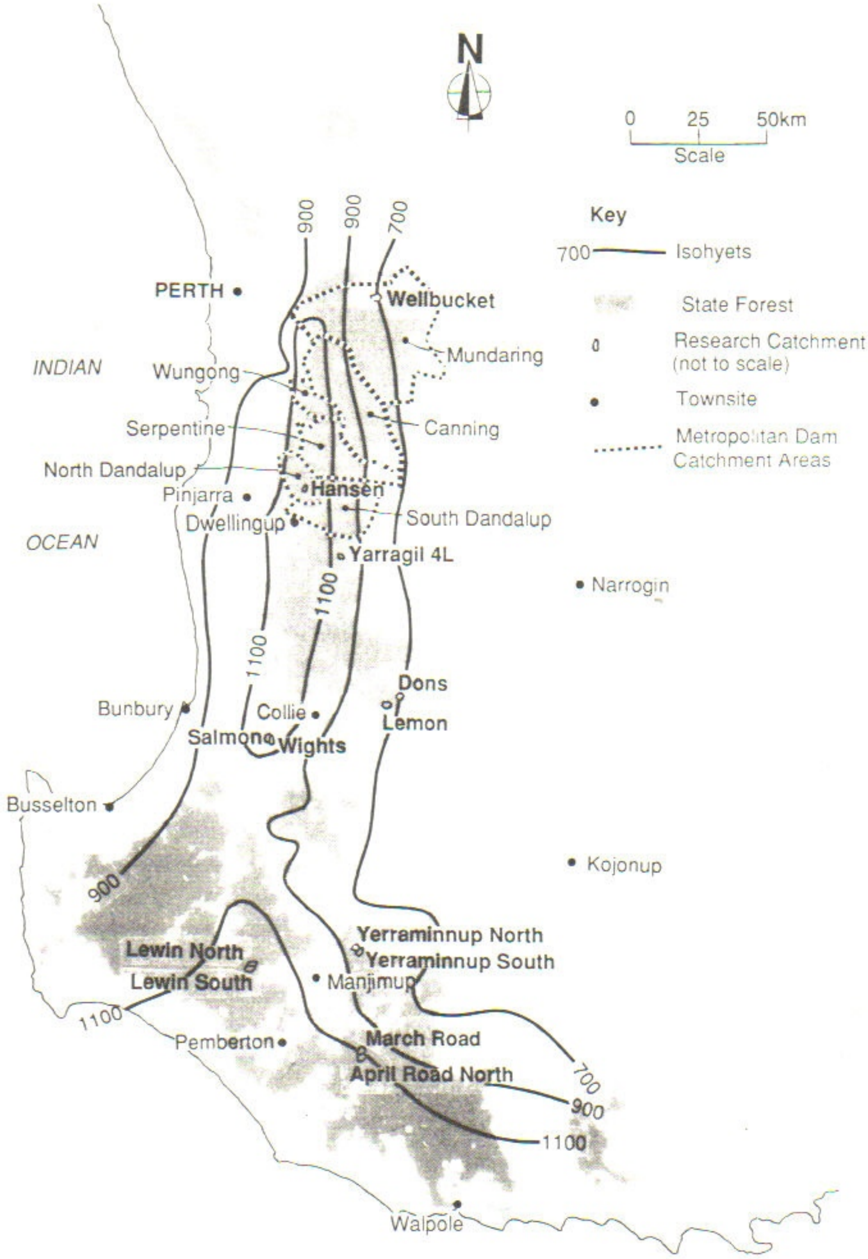

Fig. 1. Research and water supply catchments in the jarrah forest.

just north of Perth has also been shown to have a large effect on water supply (Butcher and Havel, 1976; Butcher, 1977).

Streamflow generation from forested catchments is affected by a number of factors including rainfall, vegetation type and density, soil type, geology, geomorphology, drainage, etc. The relative importance of these factors is not addressed in this paper, but local knowledge suggests that rainfall and forest density are predominant. The hydrology of the jarrah forest is described in detail by Schofield et al. (1988), and is not repeated here.

This paper describes the mechanisms of and evaluates the potential for silviculture for water production in the northern jarrah forest of Western Australia. We estimate potential streamflow increases and the contribution this could have to the Perth Metropolitan Water Supply System.

LOGGING HISTORY AND SILVICULTURAL TREATMENTS

Over 100 years of logging has converted the old-growth jarrah forest into a forest dominated by relatively young, dense stands. 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. Subsequent controlled logging was selective, and has given rise to mixed-aged 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., 1988).

Silvicultural treatments which would favour water production would involve the creation or maintenance of even-aged groups which are amenable to thinning. Treatments need to be adaptable to the present mixed range of stand structures, ages and conditions. This includes thinning of stands which have a basal area of crop trees of 10 m^2 ha^{-1} or greater for pole-sized stands, and the regeneration of stands with an inadequate density of crop trees.

AREAS AVAILABLE FOR SILVICULTURAL TREATMENT

A preliminary survey of areas suitable for silvicultural treatment in the current water supply catchments estimated that about 460 km^2 are available in the high-rainfall zone (>1100 mm $year^{-1}$ average rainfall). In the intermediate rainfall zone (between 1100 mm $year^{-1}$ and 900 mm $year^{-1}$ average rainfall) it is estimated that about 540 km^2 are potentially suitable. These areas have been derived from broad-scale forest information and probably represent a slight overestimation. A detailed inventory of forest attributes is required to refine these figures.

ANALYSIS OF POTENTIAL STREAMFLOW INCREASES

Direct catchment studies of the effects of thinning on streamflow are in the early stages. Therefore, the analysis of potential streamflow increases has relied on four indirect estimates. These are discussed in turn in the following.

Estimates from experimental catchments

(a) Agricultural clearing of jarrah forest catchments

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 ($\simeq$1200 mm year^{-1} average rainfall), were selected in the high-rainfall zone. Three catchments, Lemon, Dons and Ernies ($\simeq$800 mm year^{-1}) were selected in the low-rainfall zone (Fig. 1). Forest-clearing treatments were carried out in 1976 and were followed by the establishment of annual agricultural plant species. Experimental details and data analyses are described by Williamson et al. (1987).

Wights catchment was totally cleared and the effect on its hydrology was dramatic. Streamflow increased for 7 years following clearing and then levelled off at an increase of about 30% of rainfall (Ruprecht and Schofield, 1989).

Lemon catchment was 54% cleared. To 1983 only a small increase in streamflow had occurred, being approximately 2.1% of rainfall, or 17 mm in 800 mm year^{-1} average rainfall area. However, groundwater levels are rising rapidly and there should be significant increases in streamflow when they reach the ground surface. It is estimated that this will occur by 1990 (Hookey, 1987).

Dons catchment was 38% cleared with a mixture of parkland clearing, strip-clearing and selected soil-unit clearing in different parts of the catchment. Again a small increase in streamflow was detected, averaging 1.4% of rainfall or 11 mm in an 800 mm year^{-1} average rainfall area. As with Lemon catchment, groundwater levels are rising in cleared areas and it will be some years before the full impact on streamflow is apparent.

(b) Clearfelling, logging and thinning of jarrah forest catchments

Seven small forest catchments in the southern jarrah forest were instrumented in 1976 to determine the impact of clearfelling and logging, followed by regeneration, on water resources in the southern forest of Western Australia. Of the 7 catchments, 4 were treated in 1982/83. March Road catchment and April Road North catchment (Fig. 1) were both clearfelled, but a 100-m stream buffer (10% of area) was retained on the latter catchment. Lewin South and Yerraminnup South catchments (Fig. 1) were both heavily logged, reducing canopy cover from 70 to 10% and basal areas to 7 m^2 ha^{-1} and 5 m^2 ha^{-1}, respectively. On Yerraminnup South catchment a 50-m stream buffer was re-

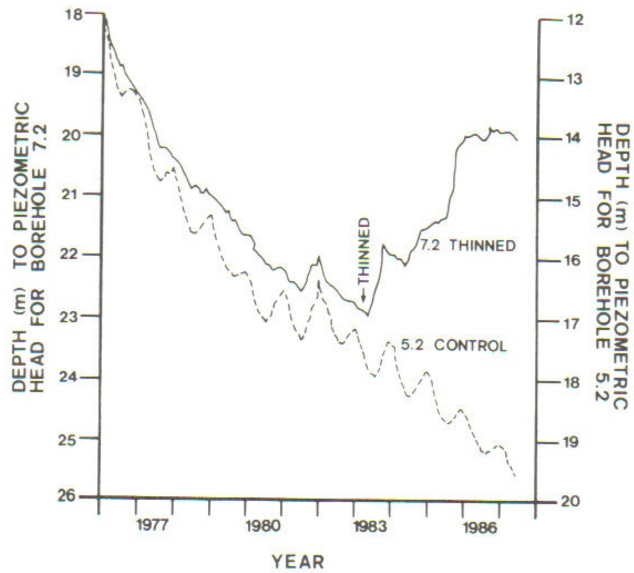

Fig. 2. Increase in borewater level in the Yarragil 4L midslope borehole following thinning in comparison to a control borehole.

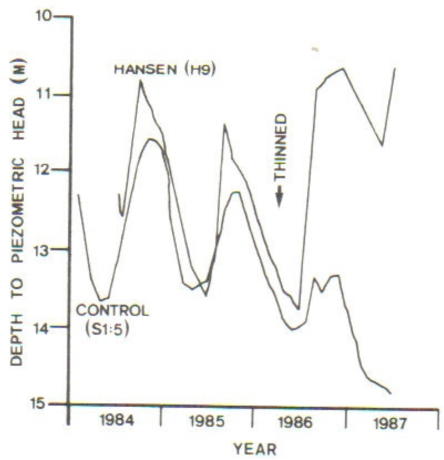

Fig. 3. Borewater level for a Hansen catchment borehole and a control borehole, before and after thinning.

tained, which accounted for 12% of the catchment area. Experimental details and results to 1986 are described by Borg et al. (1987).

On all the treated catchments, highest streamflow increases, expressed as percentage of rainfall, occurred within 2 years of treatment. The reduction in streamflow increase in 1985 and 1986 reflects forest regeneration (Borg et al., 1988).

The average streamflow increase on Lewin South catchment (1982–1985, 1230 mm $year^{-1}$ average rainfall) was 116 mm, or 9.5% of rainfall. The streamflow increases for March Road (1040 mm $year^{-1}$ average rainfall) and April Road North (1070 mm $year^{-1}$ average rainfall) catchments are slightly greater than that of Lewin South catchment, despite lower rainfalls. This is attributed to these catchments being clearfelled. The average increases for these catchments over the same period were: March Road, 11.3% of rainfall or 121 mm; April Road North, 9.7% of rainfall or 104 mm.

Yerraminnup South catchment (830 mm $year^{-1}$ average rainfall) in the low-rainfall zone produced somewhat smaller streamflow increases in response to heavy logging. The 1982–1985 average increases were 2% of rainfall, or 20 mm.

A paired-catchment study in the east of the Helena catchment (700 mm $year^{-1}$ average rainfall) investigated the effect of logging on catchment hydrology (Stokes and Batini, 1985). Of the 2 catchments, Wellbucket was logged in 1977 and Yarra (Fig. 1) was a control. The logging resulted in a reduction of canopy density from 38 to 20% and in basal area from 16 m^2 ha^{-1} to 11 m^2 ha^{-1}. There was no significant increase in streamflow and no change in groundwater level as a result of the logging.

Yarragil 4L catchment (1120 mm $year^{-1}$ average rainfall) was thinned in 1983 (Stoneman, 1986). Canopy cover was reduced from 55 to 20%, basal area over bark (BAOB) from 35 m^2 ha^{-1} to 11 m^2 ha^{-1} and leaf area index from 1.9 to 0.6. In the first 2 years after thinning there were only minimal increases in streamflow, but in the 3rd year the increase was more significant. The groundwater table at a midslope location has risen 1 m $year^{-1}$ since thinning (Fig. 2); this implies that further increases in streamflow will occur for some time.

Hansen catchment (1340 mm $year^{-1}$ average rainfall; Fig. 1) was thinned from 35 m^2 ha^{-1} to 7 m^2 ha^{-1} in 1985. In the 1st year following thinning there was a significant streamflow increase of 40 mm despite the very low 1986 rainfall. The groundwater table at a midslope location has shown a substantial rise in the 15 months since the thinning (Fig. 3).

(c) Discussion of experimental catchment results

A summary of the catchment results is given in Table 1. Three major points are evident:

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

TABLE 1

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			Max annual streamflow increase		Groundwater at surface
					mm	% rain	% flow	mm	% rain	
Wights	1200	Agricultural development	PCF100-0	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 Rd	1070	Clearfelling & regeneration	CC 65-0	1982-85	121	11.3	147	196	18.3	Yes
April Rd North	1070	Clearfelling leaving 100 m 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 L 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^{-1}), PCF = percentage of catchment forested, L = leaf area index.
*See Fig. 1,

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

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

In the high-rainfall zone, Hansen and Yarragil 4L catchments have been thinned. Both of these catchments have shown a significant but relatively small streamflow response to thinning. In the case of Hansen catchment there is only 1 year's data available, and that was a year of very low rainfall. In Yarragil 4L catchment the groundwater table was at some depth below the stream and the small streamflow increases so far are attributed to increasing soil-water storage.

Wights catchment was cleared for agriculture, and may be considered representative of the high-rainfall zone for total forest clearing with no regeneration. The streamflow increase in this case was about 30% of rainfall, or 360 mm.

Lewin South catchment, in the high-rainfall zone of the southern forest, was intensively logged and regenerated. The basal area after logging is the least that would be anticipated for silviculture for water production. Groundwater was at the ground surface within the catchment and an immediate streamflow response would be expected. Regeneration was rapid, and combined with an increase in soil-water storage, would have decreased streamflow. Rainfall for the post-treatment monitoring period was 86% of the long-term average. Despite the obvious complications, this catchment's streamflow response was considered the most representative for the high-rainfall zone. The appropriate estimate of streamflow increase was taken to be the average increase of the first 3 full calendar years (1983–1985) following treatment. This was 11.5% of rainfall, or 138 mm.

In the intermediate-rainfall zone, March Road and April Road North catchments are representative of the upper limits of thinning because they were clearfelled. However, this is offset to some extent by regeneration and, in the case of April Road North, the retention of a stream buffer. Both catchments have groundwater intersecting the ground surface at some locations in the catchment. The 1983–1985 average streamflow increase for April Road North was assumed to be the most representative for the intermediate rainfall zone. Streamflow increase was 11.9% of rainfall, or 119 mm.

The four catchments in the low-rainfall zone, Yerraminnup South, Lemon, Dons and Wellbucket, typically show little streamflow response to reduction in forest density. Groundwater levels in cleared or partially cleared areas of Lemon and Dons catchments are rising and may eventually reach the soil surface, leading to further increases in streamflow.

Estimates from canopy-cover streamflow relationships

The relationship between streamflow and canopy cover for 6 high-rainfall-zone catchments (1300–1350 mm $year^{-1}$ average rainfall) is shown in Fig. 4. The effect of reduced canopy cover on streamflow is both clear and dramatic.

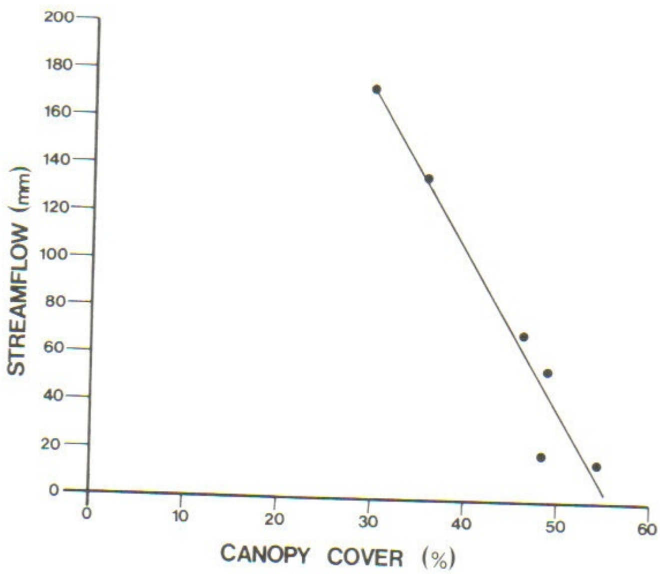

Fig. 4. Relationship between canopy cover (%) and streamflow (mm) for six catchments in the high-rainfall zone of the northern jarrah forest.
$y=371-6.678x \quad r^2=0.94$

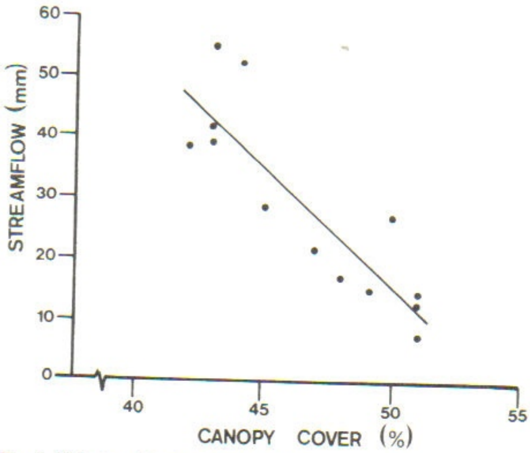

Fig. 5. Relationship between canopy cover (%) and streamflow (mm) for 13 subcatchments of the Yarragil catchment in the intermediate-rainfall zone of the northern jarrah forest.
$y=208-3.83x \quad r^2=0.75.$

The relationship between streamflow and canopy cover for a selected subset of intermediate-rainfall-zone Yarragil Brook subcatchments with similar physical characteristics (i.e. catchments with similar landforms, soils, shape, slope and aspect) is shown in Fig. 5. The effect of reduced canopy cover on streamflow is again clear.

The relationship for the high-rainfall zone (Fig. 4) predicts a streamflow increase of 237 mm or 18.2% of rainfall by reducing canopy cover from 50 to 20%.

The relationship for the intermediate-rainfall zone (Fig. 5) predicts a streamflow increase of 115 mm (11.5% of 1000 mm rainfall) by reducing canopy cover from 50 to 20%.

However, the canopy-cover differences between catchments are mainly due to dieback (especially for high-rainfall-zone catchments). There may be some bias in generating streamflow because dieback occurs preferentially in valley bottoms and is also associated with areas of higher lateral soil water flow (Shea et al., 1983).

Estimates from water balance changes

An estimate of the streamflow (W) of a catchment can be made from knowledge of other water balance components, viz.

$$W = P - E - I + \Delta S \qquad (1)$$

where P is rainfall, E is transpiration from vegetation and evaporation from soil, I is interception and ΔS is the change in soil water content. The change in streamflow due to thinning can be calculated from equation (1) if it is assumed there is no long-term change in understorey or soil water evaporation and soil water storage. The change in streamflow is then given by:

$$\Delta W = \Delta T_o + \Delta T_h - \Delta S_t \qquad (2)$$

where ΔT_o is change in overstorey transpiration, ΔT_h, change in throughfall, and ΔS_t, change in stemflow. Estimates of ΔT_o, ΔT_h and ΔS_t are determined below.

(a) Effect of thinning on overstorey transpiration

McNaughton and Jarvis (1983) argue that, because transpiration rate from a forest is largely determined by vapour pressure deficit, then the transpiration rate after thinning a forest could be expected to be reduced in approximately the same proportion as the reduction in leaf-area index (L).

The effect of thinning on tree and stand leaf-area has been studied in a jarrah thinning experiment. Various dimensions and characteristics of selected trees were measured. The trees were felled, all leaves harvested and tree leaf-area measured. Dimensional relationships to predict the leaf area of individual trees

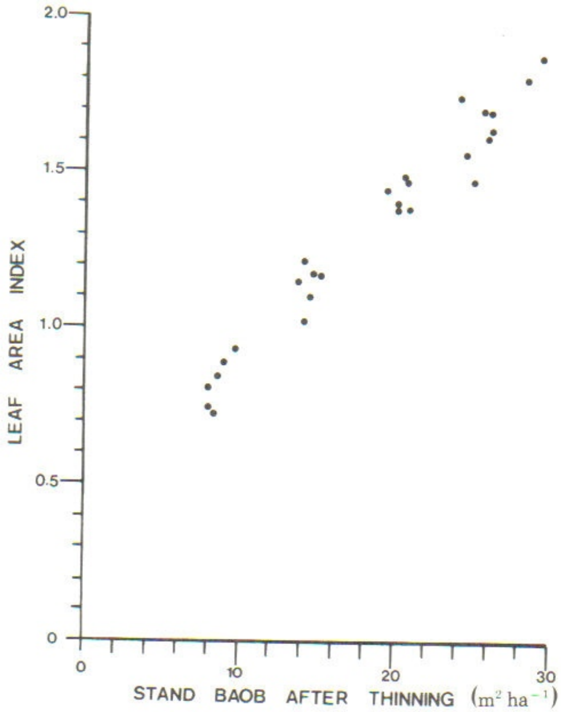

Fig. 6. Effect of stand basal area over bark (m^2 ha^{-1}) on stand leaf-area index for a 61-year-old jarrah stand 21 years after thinning.

have thus been established and these have been used in the thinning plots to predict stand leaf-area. Figure 6 shows the effect of thinning on stand L 21 years after the thinning. Stand L is still substantially lower in thinned than unthinned stands. Thinning to 10 m^2 ha^{-1} BAOB resulted in a stand with L of 0.90 in comparison to an unthinned stand at 30 m^2 ha^{-1} BAOB with L of 1.90, a net reduction in L of 53%.

The overstorey transpiration of a jarrah forest site has been estimated at 35% of rainfall (data not presented). Assuming transpiration rate is proportional to L, then ΔT_o would be 18.5%.

(b) Effects of thinning on throughfall

Throughfall was measured over the winter of 1985 in a 60-year-old regrowth jarrah stand which had been thinned to a range of stand densities 21 years previously. There was a strong relationship between stand basal area under bark (BAUB) and throughfall (Fig. 7). There was also a strong relationship between stand L and throughfall ($y = 100.0 - 12.045\ x$, $r^2 = 0.973$). The BAUB

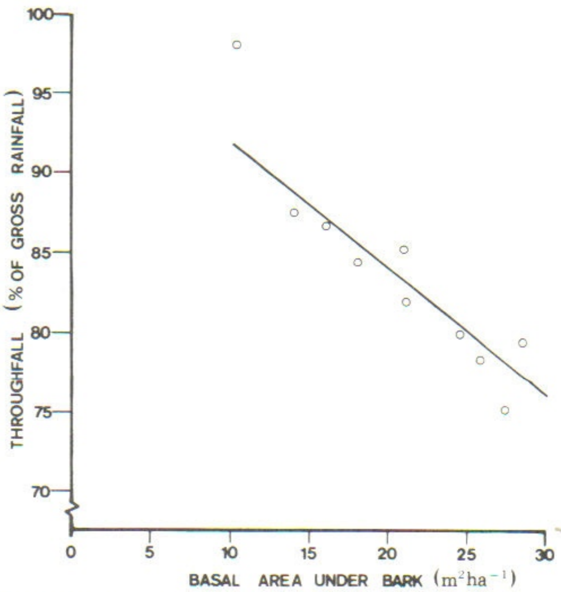

Fig. 7. The effect of stand basal area under bark (m^2 ha^{-1}) on throughfall (as a percentage of gross rainfall) for a 61-year-old jarrah stand 21 years after thinning.
$y = 100.0 - 0.80x$ $r^2 = 0.98$.

throughfall relationship predicts that throughfall would increase by 12.4% of rainfall due to thinning from 23 m^2 ha^{-1} BAUB ($\simeq 30$ m^2 ha^{-1} BAOB) to 7.5 m^2 ha^{-1} BAUB ($\simeq 10$ m^2 ha^{-1} BAOB) (where BAOB $= 1.3 \times$ BAUB). Thinning over this range would result in $\Delta T_h = 12.4\%$.

(c) Effects of thinning on stemflow

There are as yet no data on the effects of forest thinning on stemflow in the jarrah forest, though we have estimated that about 5% of rainfall could be attributed to stemflow at a site in the high-rainfall zone. Assuming that stemflow is proportional to basal area, then $\Delta S_t = 3.5\%$.

(d) Calculation of water balance changes

Substituting the above values of ΔT_0, ΔT_h and ΔS_t into equation (2) gives a streamflow increase of 27.4%. This estimate of ΔW approaches that observed due to total clearing for agriculture, and may therefore be unrealistic. The failure of the water balance equation to give a realistic estimate is partly due to the assumptions made. In reality, the annual evaporation of a thinned forest may be greater than suggested due to increased understorey transpiration, soil water evaporation, and increased overstorey transpiration per unit leaf area. Soil moisture and groundwater stores of water may also absorb some of the estimated increases in streamflow.

Estimates from model simulations

The Darling Range Catchment Model (DRCM; Mauger, 1986) has been used to simulate the effects of thinning in the Canning catchment (Hammond, 1987) and the Yarragil 4L catchment. In the Canning catchment simulation, the model was calibrated on rainfall and streamflow data for the period 1912–1983. The simulated and observed flows were closely matched, with total volumes for the period being within 7%. In the assumed thinning simulation, only the north-western high-rainfall portion of the catchment was considered. This area was 32% of the whole catchment and contained 147 km^2 (64%) of forest suitable for thinning for water production. Two thinning scenarios were devised and translated to leaf-area-index functions for the modelling period. The simulated increases in streamflow for the two thinning scenarios are summarised in Table 2. The mean annual rainfall for the period was assumed to be 1000 mm $year^{-1}$.

The simulation involved thinning at approximately 30-year intervals and thus catered to some extent for longer-term periodic fluctuations in forest density. The average streamflow increase for the two thinning scenarios considered was 11.5% of annual rainfall. This result is considered to be the more representative of the modelling estimates for the intermediate-rainfall zone.

DRCM was also used to simulate the effects of the 1983 logging of the Yarragil 4L catchment. The model predicted only small increases in streamflow in the first few years, but after 4–5 years substantial increases occurred. Over the period 5–10 years following thinning, streamflow increases would be approximately 125 mm $year^{-1}$ (11.2% of rainfall). Over a 15-year period, streamflow for the unthinned catchment was predicted at 150 mm, whereas for the thinned catchment it was predicted at 1030 mm, an increase of 880 mm or nearly 60 mm $year^{-1}$. The results from the model were strongly dependent on the assumed rate of leaf-area increase following thinning. The growth rate used

TABLE 2

Results of simulations of thinning in the Canning catchment over the period 1911–1984

Obs.[a] flow (mm)	Simulation 1			Simulation 2		
	mm	Sim./Obs.	Increase % rain	mm	Sim./Obs.	Increase % rain
145.2	270	1.86	12.5	248.7	1.71	10.4

[a] Obs., observed; Sim., simulated.

in the model may be higher than occurs naturally and as a consequence predicted streamflow increases may be conservative.

Summary of estimated changes in streamflow

Four different methods of estimating streamflow increase have been described above. The results thought to be most representative of thinning are summarized in Table 3. Although each individual estimate has relatively low reliability, all methods estimate substantial increases in streamflow. The most conservative estimate for the high-rainfall zone and intermediate-rainfall zone was 11.5% of rainfall.

Limitations of analysis

In practice, the silvicultural treatment of stands for water production would involve a number of different treatments. Stands would have different densities prior to treatment, immediately following treatment, and would have different responses to treatment. It is not possible at this time to include all of these factors in an evaluation of the effects on streamflow.

ESTIMATED STREAMFLOW INCREASES IN WATER SUPPLY CATCHMENTS

The water supply catchments for Perth are shown in Fig. 1. Individual catchment streamflow increases have been estimated by multiplying the area of the catchment suitable for silviculture for water production by the lowest esti-

TABLE 3

Summary of estimates of streamflow increase resulting from thinning

Method	Streamflow increase			
	High-rainfall zone		Intermediate-rainfall zone	
	(mm year^{-1})	(% rainfall)	(mm year^{-1})	(% rainfall)
Experimental catchments	138	11.5	119	11.9
Canopy cover relationships	218	18.2	115	11.5
Water balance changes	329	27.4	274	27.4
Modelling	138	11.5	115	11.5
Mean	206	17.2	156	15.6
Minimum	138	11.5	115	11.5

mated streamflow increase for each rainfall zone (Table 3). The estimated streamflow increases from these catchments range from 25 to 81% of long-term mean annual flows (Table 4). The estimated total streamflow increase amounts to 127 million m^3 $year^{-1}$ of 47% of the long-term mean annual flow. This amount is approximately equally divided between the high-rainfall zone and the intermediate-rainfall zone.

Estimated reservoir yield increases

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, personal communication, 1987). A variety of options have been tested, and are summarised in Table 6. With the current limitation 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 would increase to 53% if the trunk main capacities were to be upgraded. If only the high rainfall portion of the area available for thinning is included, then 57% of the estimated streamflow increase would be utilized. With the current trunk main capacity, this represents 77% of the increased yield from both high and intermediate-rainfall zones.

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 m^3 $year^{-1}$, or 53% of the estimated streamflow increase for this catchment, is potentially available.

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 1000 km^2. The cost of silvicultural treatment has been estimated to range from \$1100 to \$3700 km^{-2}, averaged over 15 years (depending on the type of treatment carried out and the level of utilization of wood products from thinning). On this basis, the cost of producing the estimated 48 million m^3 $year^{-1}$ would range from A\$0.023–0.079 cents m^{-3}. If the high-rainfall zone only was treated, the cost of producing the estimated yield increase of 37 million m^3 $year^{-1}$ would range from A\$0.014–0.047 cents m^{-3}. Both of these costs compare favourably with the

TABLE 4

Estimated streamflow increases for individual water-supply catchments

Catchment	Total area (km^2)	Area to be treated		Streamflow annual avg. increase				Current annual avg. streamflow (1911-1986)		Estimated annual avg. streamflow increase		
		HRZ[a]	IRZ[b]	HRZ		IRZ		(mm)	(10^6 m^3)	(mm)	(10^6 m^3)	(%)
		(km^2)	(km^2)	(mm)	(10^6 m^3)	(mm)	(10^6 m^3)					
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

[a]High-rainfall zone (1200 mm $year^{-1}$).
[b]Intermediate-rainfall zone (1000 mm $year^{-1}$).

TABLE 5

Reservoir storage to inflow ratios

	Mundaring	Canning	Wungong	Serpentine	N. Dandalup*	S. Dandalup
Storage: inflow ratio	1.6	1.5	2.2	2.5	2.5	5.0

*Proposed dam

TABLE 6

Simulated increases of water supply system* for a range of options

Option	Simulated increase in system water supply			
	With current trunk mains		With upgraded trunk mains	
	(10^6 m^3 year^{-1})	(%)	(10^6 m^3 year^{-1})	(%)
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. Dandalop only (25.8 million m^3)	13.6	53	16.2	63

*Simulations assume construction of N. Dandalup dam completed (1993)

development of a new dam, the cheapest of which would provide water at A$0.20 m^{-3} (Mauger, 1987).

CONCLUSIONS

Silvicultural treatments of the Perth Metropolitan Water Supply Catchments have the clear potential to significantly increase catchment water yield.

The area of water supply catchments available for silvicultural treatment for water production is estimated at 1000 km^2. Of this, 460 km^2 lie in the high-rainfall zone and 540 km^2 lie in the intermediate-rainfall zone.

Three of the 4 indirect estimates of streamflow increase following silvicultural treatment for water production were considered to give reasonable results. The values ranged from 11.5–18.2% of rainfall (approximately 140–220 mm of streamflow) for the high-rainfall zone. For the intermediate-rainfall zone, the values ranged from 11.5–11.9% of rainfall (approximately 115–120 mm of streamflow). Whilst each estimate individually was considered to have relatively low reliability as a predictor of streamflow increase following thinning, the three estimates are reasonably similar.

The total streamflow increase was calculated at 127 million m^3 $year^{-1}$, or a 47% increase of the current average streamflow. This calculation was based on the total estimated area suitable for treatment (1000 km^2) and the minimum 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 m^3 $year^{-1}$ increased streamflow, only 48 million m^3 $year^{-1}$ would be utilized by the Perth Metropolitan Water Supply System because of spillage, evaporation and trunk main capacity factors. If the high-rainfall zone alone was treated, 37 million m^3 $year^{-1}$ of the 65 million m^3 $year^{-1}$ estimated streamflow increase would be utilized by the water supply system.

The cost of producing the estimated total utilizable yield would be in the range A\$0.023–0.079 m^{-3}. For the estimated increased water yield from the high-rainfall zone only, the cost range would be A\$0.014–0.047 m^{-3}. In both cases the cost compares favourably with the alternative of developing new sources in the jarrah forest at a minimum cost of A\$0.20 m^{-3}.

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, and lower cost.

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