The Impact of Logging on the Water Resources of the Southern Forests, Western Australia

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

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Introduction

The timber industry in the southern forests of Western Australia traditionally only produced sawn timber. Non-sawlog grade logs of karri, jarrah, and marri, and milling residues were not utilised.

Clearfelling, especially of karri, was recognised as the most appropriate logging technique early in the century. It facilitated regeneration and created easily managed even-aged regrowth forests. Though commonly practiced in the karri forest in the period up to 1940, the cost and waste of felling and burning non-commercial trees were major factors in the discontinuation of clearfelling after that time. These factors were largely eliminated when a commercial use of non-sawlog quality karri and marri as chipwood for paper pulp was developed in the late 1960s. By this time, however, the value of the water resources in southern forests and the risk of salinity had become well known. There was concern that the re-introduction and more widespread use of clearfelling in the karri and more intensive logging in the jarrah forest might affect water quality.

The Environmental Impact Statement on the proposed woodchipping industry in the Manjimup Woodchip Licence Area (Forests Department, 1973) recognised some risk to water quality. It was decided that the industry should proceed but that research should be undertaken to quantify water quality effects. A Steering Committee was formed in 1973 under the chairmanship of Mr K.J. Kelsall to monitor water quality, identify areas prone to stream salinisation and to provide the Forests Department with technical data on which to base management. This report reviews research carried out over the period 1975-86 and provides conclusions and recommendations for management.

Research Programme

The main objectives of the research programme were:

- to determine the magnitude and duration of any increase in stream salinity and sediment concentration resulting from the proposed logging operations;
- to consider the long term effects (20 to 100 years) of logging and regeneration on water yield; and
- to propose, if necessary, improved logging practices to preserve water quality.

The programme involved the establishment during 1975 and 1976 of eleven research catchments which spanned the rainfall zones and forest types of the region. Rainfall, the quality and quantity of stream discharge and groundwater responses were monitored on all catchments. Four catchments were logged and regenerated during 1977 and 1978 to obtain an early indication of any serious environmental effects during the early years of the new cutting regimes. While limited pre-treatment data are available, this early-warning project now has eight years of post-treatment data.

A further four catchments were logged and regenerated in 1982 and 1983. In this more detailed paired-catchment project, at least 6 years of pre-treatment data were collected. Three catchments were left untreated as controls so that changes in surface and groundwater hydrology caused by the logging could be separated from changes caused by climatic variation. Three years of post-treatment data are now available.

Treatments applied in the early-warning project were the normal operational practice of clearfelling of karri stands and a heavy selection cut of sawlogs and chiplogs in jarrah-marri stands. In the paired-catchment project, an additional silvicultural treatment was carried out on two jarrah-marri catchments to remove unwanted trees while retaining groups of trees with potential to grow into good quality timber.

One catchment in each project was located in the low rainfall, north-east sector of the licence area to evaluate the effects of the new logging strategies in this zone with high soil salt storage. The effect of the presence or absence of stream reserves and winter and summer logging in karri stands were also evaluated through the paired-catchment project.

Results and Discussion

Rainfall for the study period (1975-85) was 10% below the long term mean. The drier conditions are likely to have lessened the magnitude of the hydrologic response to logging and regeneration, but not the general trends. Care has been taken to account for this effect when interpreting the results and formulating recommendations.

The vegetation regenerated quickly in all rainfall zones. In karri stands vegetation cover approached pre-logging levels within 5 to 10 years and while actively growing to maturity would achieve higher densities than the original mature forest unless thinned. Jarrah-marri stands responded more slowly, reaching 90% of pre-logging cover in about 10 to 15 years.

Groundwater Responses

In the early-warning project catchments, permanent groundwater levels (relative to control bores) rose in all cases for two to four years after logging and then started to decline. The groundwater levels were still higher than pre-logging values eight years after logging, but are continuing to decline. Assuming current rates of decline, it will take a further five years for the permanent groundwaters to return to the level they would have been without logging. Three years after the commencement of regeneration on the treated paired catchments, groundwater levels are approaching their peak or beginning to decline on the jarrah-marri catchments but have yet to reach their peak on karri catchments.

Results from both projects showed that groundwater responses to logging were much less in areas with a long term average rainfall less than 900 mm per annum (low rainfall region) than in areas with greater than 900 mm per annum (intermediate and high rainfall regions).

Stream Salinity Responses

Small increases in annual flow-weighted stream salinities of between 50 and 150 mg/L Total Soluble Salts occurred on most treated experimental areas. However all annual flow-weighted salinities remained below 500 mg/L Total Soluble Salts, the limit for high quality drinking water. In the early-warning project, maximum annual stream salinities occurred two years after regeneration commenced, and salinities have since declined. In the paired-catchment project, annual salinities were highest in 1985, two years after the commencement of regeneration. The largest increase in annual flow-weighted salinities (approximately 150 mg/L Total Soluble Salts) occurred on a clearfelled catchment in the intermediate rainfall zone (900-1100 mm per year) which did not have a stream vegetation buffer. Salinity during periods of low flow on this catchment increased from 700 mg/L pre-logging to more than 1500 mg/L post-logging, although these values occurred only during a few weeks following the commencement of winter flow.

At the outset of the research programme, there was particular interest in the effect that the new logging strategies could have on water quality in the north-eastern low rainfall (<900 mm per year) sector of the Woodchip Licence Area where the soil salt storage is high. However, experimental results have shown that there was no stream salinity increase in this area because recharge was small and the depth to groundwater was sufficiently large such that groundwater (the major source of salt) did not contribute to streamflow following logging.

In the intermediate and high rainfall zones, groundwater contributed to streamflow prior to logging. Following logging in these zones, permanent groundwater levels rose and stream salinities increased, indicating an increase in the discharge of salts from groundwater to streams. Similarly, as groundwater levels began to fall following regeneration, stream salinities fell. It is anticipated that stream salinities will return to near pre-logging values.

From a regional water resource perspective, temporary salinity increases of the magnitudes encountered are minor. However the low flow salinities measured at greater than 1500 mg/L, if they persist for many weeks, could cause problems with small-scale public water supply systems based on low-volume storages. This problem can be overcome by appropriate design of vegetative stream buffers.

Sediment Concentrations
Stream sediment concentrations prior to logging were less than 5 mg/L in all monitored catchments. Sediment concentrations increased on two of the four paired catchments and remained elevated for one to two years following logging, before declining to pre-logging levels over the next three years. The catchments where measurable increases in sediment concentrations occurred had no buffer of streamline vegetation retained and were logged through the winter periods. The highest annual flow-weighted sediment concentrations were 38 mg/L and 20 mg/L. No sediment increases were detected on the catchments which were logged during dry summer conditions only and which had a buffer of streamline vegetation retained.

In a regional water resources context, the sediment increases were minor, due in part to the practice of wide dispersal of the logging operations. These stream sediment increases would be of concern to a drinking water supply storage of small volume and short retention time as insufficient time would be available for turbidity levels to reduce in the storage.

Water Yield
Streamflow volumes increased at all sites for two to three years after logging and then began to decline. The paired-catchment results indicated a doubling of streamflow volumes in these early years. In the high and intermediate rainfall zones, these increases were about 10% of rainfall, whereas in the low rainfall zone the increase was less than 5% of rainfall. Results from the early-warning project catchments suggest that streamflows will return to pre-logging levels in about 12 years. If all stands were subsequently left unthinned, a significant reduction in water yield could result.

Implications for management

Analysis of research results currently available indicates that logging methods involving clearfelling of karri and heavy selection cutting of jarrah have minor effects on stream salinity and sediment concentrations. No major changes to management practice are necessary. However, transient effects on stream salinity and sediment concentrations could be locally significant and could be moderated by refinements to management practice. Such refinements should be progressively developed and implemented.

The refinements outlined here are categorised by rainfall zone. They are based on the research results presented in this report and experience gained from similar studies elsewhere.

High rainfall zone: Refinement to management should focus on improving sediment control using methods which do not exclude utilisation of timber resources or involve significant extra costs. The options available include:

(i) redistribution of existing road, river and stream reserves to increase reserves along streamlines;
(ii) exclusion of forest operations likely to cause significant soil or understorey disturbances from a buffer along all streamlines for the period of upslope logging operations and for at least three years following upslope regeneration (termed phased logging operations);
(iii) improvement in scheduling of logging and road construction to further limit winter operations in the most sensitive areas;
(iv) further improvement in the location, construction and maintenance of logging roads.

Intermediate rainfall zone: The potential for increase of stream salinity resulting from logging is greatest in this zone, although this potential varies considerably within the zone. In order to refine management in this zone, a method is required to identify areas where the risk of increased stream salinity is high. This method should provide an estimate of depth to the permanent groundwater and the storage of soil salt in the zone of potential groundwater rise along valley bottoms. Research results indicate that stream vegetation buffers would reduce the rate of groundwater rise and should be employed where salinity risk is greatest. The size of the buffer should be commensurate with the salinity risk. If substantial buffer areas appear desirable, phased logging of such areas could be undertaken about ten years after the commencement of regeneration of upslope areas, although the exact phase delay required is yet to be determined.

Stream sediment control remains an important objective in this zone. Sediment can be controlled by the options described for the high rainfall zone.

Low rainfall zone: For much of this area the depth to groundwater under forest is sufficiently large and the recharge from rainfall sufficiently small for logging operations to take place without risk of increasing stream salinity. However there is a need to identify areas where permanent groundwaters could rise to the surface following intensive logging and to provide these areas with substantial stream buffers (greater than 10% of the upslope logged area) which would be permanently excluded from any intensive logging operations. Current research results indicate that the safe depth to groundwater for logging to proceed, with buffers, is five metres (annual minimum permanent groundwater level below stream bed).

Conclusions

1 : In the high and intermediate rainfall zones, logging operations have caused small and temporary increases in stream salinity and/or sediment concentration in many local streams but this presents no significant threat to regional water resources.

2 : Further refinement of logging practice is possible to moderate local transient effects on stream salinity and sediment concentration.

3 : With appropriate management, there is no significant stream salinity risk from heavy selection cutting in the low rainfall north-east sector of the Woodchip Licence Area.

Recommendations

1 : Woodchipping operations can proceed in the north-east sector of the Licence Area subject to the implementation of recommendations 2 and 3.

2 : Practical techniques for the identification of local salt-sensitive areas in the intermediate and low rainfall zones should be developed and implemented.

3 : Methods to control deep groundwater contribution to streamflow should be refined and incorporated into practice in the salt-sensitive areas of the intermediate and low rainfall zones. Methods include the greater use of stream buffers and phased logging operations.

4 : Methods to further reduce any temporary increase of stream sediment concentration should be developed and incorporated into operations. Methods include improved road location and design, more extensive use of stream buffers, phased logging operations and limiting winter operations in the most sediment sensitive areas.

5 : The current level of monitoring of research catchments should continue with a further major review in 1990. Monitoring and evaluation should be carefully conducted to guide operational development, especially with respect to phased logging and permanent groundwater management.

6 : Management prescriptions to protect water quality and quantity should be regularly modified in response to improved understanding gained through research and operational experience.

1. Introduction

Logging of timber in the southern forests of Western Australia has been in progress for over 80 years. The various methods of logging and regeneration of forest used over this period have been described by Bradshaw and Lush (1981) and Borg *et al*, (1987). In the mid 1960s the Forests Department of Western Australia wished to return to the intensive logging methods used earlier this century to promote more vigorous regeneration of karri *(Eucalyptus diversicolor)* and jarrah *(E. marginata)* forests. The development of a woodchip industry to utilise non-sawlog grade marri and karri facilitated this proposal. In 1969 the State Government passed the Woodchipping Industry Act which set out the responsibilities of the State to provide a chipwood resource and the W.A. Chip and Pulp Company Pty. Ltd. to establish a chip mill to process the product for export.

As an export licence was required, environmental approval from both the Commonwealth and State Governments was necessary for the project to proceed. The Environmental Impact Statement on the project (Forests Department, 1973) recognised that under certain conditions the proposed logging operations might adversely affect the quality of surface water resources. This concern stemmed primarily from the increase in stream salinity that had resulted from agricultural development of forest areas (Wood 1924, Peck and Hurle 1973). Although more than 80 years of experience with logging and subsequent regeneration of the forest suggested little cause for concern, the generally more intensive operations proposed involved sufficient uncertainty to warrant a research programme to quantify the effects.

In 1973 a technical Steering Committee for Research on the Woodchip Industry was formed under the Chairmanship of Mr K.J. Kelsall. The research programme established by that committee is now the responsibility of the Steering Committee for Research on Land Use and Water Supply, a body responsible to the State Government through the Co-ordinating Committee for Research on Land Use and Water Supply. Prior to the establishment of the research programme, no quantitative information was available on how logging operations affect stream salinity or stream sediment concentration. The research programme was set up to quantify both the short-term and long-term effects of the proposed new logging operations.

This report reviews the results of research over the period 1975-86 and provides an overview to a number of more detailed technical reports listed below:

TECHNICAL REPORTS

1. Forest density response following intensive logging operations in the southern forest of Western Australia, G.L. Stoneman, P.W. Rose and H. Borg (1987).
2. Review of the Effects of Logging on Groundwater in the Southern Forests of Western Australia - Project 2 Paired Catchment Study, M.W. Martin (1987).
3. Stream and groundwater response to logging and subsequent regeneration in the southern forest of Western Australia: Results from four experimental catchments, H. Borg, G.L. Stoneman and C.G. Ward (1987).
4. Research into the effects of logging and subsequent regeneration on water resources in the southern forest of Western Australia : Interim results from paired catchment studies, H.Borg and I.C. Loh (1987).

2. *Description and History of the Woodchip Licence Area*

Location, Climate and Vegetation

The Woodchip Licence Area is centred on the town of Manjimup (Figure 1) and covers 884 100 hectares of the southern forests, defined here as the forested land of Western Australia which drains into the Southern Ocean. The mean annual rainfall across the licence area ranges from over 1400 mm in the south-west to less than 700 mm in the north-east. About 80% of the annual precipitation occurs from May to October. The mean annual pan evaporation varies from 1150 mm in the south-west to 1450 mm in the north-east. In contrast to rainfall, pan evaporation is lowest in winter and highest in summer. In winter, rainfall exceeds pan evaporation and in summer, pan evaporation exceeds rainfall. This is illustrated in Figure 2, together with other climatic characteristics of the region which also change systematically with distance from the coast.

Within the area are 176 600 hectares of karri forest, and 418 800 hectares of jarrah forest. This is equivalent to 94% of all karri forest and 20% of all jarrah forest in the State. Karri is the principal species where the mean annual rainfall exceeds 1100 mm. It does not appear where the mean annual rainfall is less than 1000 mm (Churchill, 1967) and is virtually restricted to loamy soils. Jarrah dominates the areas with 650 mm to 1100 mm mean annual rainfall, but is also present in higher rainfall areas where site conditions are not suitable for karri. About a third of the karri forest occurs in pure stands, and the remainder in association with marri *(E. calophylla)*, jarrah, red tingle *(E. jacksonii)* and yellow tingle *(E. guilfoylei)*. Most of the jarrah forest is, in fact, a jarrah-marri mixture. The proportion of jarrah or karri to marri varies between sites, but approximately equal proportions are not uncommon (Forests Department, 1973). A detailed description of the vegetation in the region is given by Smith (1972) and Bradshaw and Lush (1981).

Logging Operations and Forest Management

Logging in the southern forests began before the turn of the century. Planned forest management began some years later with the formation of the Forests Department in 1918. Access to timber resources was regulated and managed regeneration of cut-over areas introduced. Clearfelling was adopted in karri forest in response to the high proportion of sawlog quality trees in pure karri stands, and the evidence of superior regeneration in stands logged by this practice as early as 1880. In contrast, selection cutting was appropriate in jarrah forest because of the small proportion of sawlogs and jarrah's capacity to regenerate satisfactorily in the presence of competition from mature trees.

By the 1940s a range of factors caused a change to selection cutting in karri. The major factors were war-time labour costs, the waste inherent in felling and burning non-commercial trees, renewed pressure for release of clearfelled areas for agriculture and the value in extracting scattered, overmature, declining trees before their death. The importance of these factors diminished over time and by the 1960s the benefits of clearfelling, particularly the greater vigour and ease of management of even-aged regeneration, were again ascendant and clearfelling was recommenced. The balance was thrown decisively in favour of clearfelling (and of more intensive selection cutting in jarrah forest) by the development of a commercial use for non-sawlog grade karri and for the previously unused marri. This use was for chipwood production for export for paper pulp. Integrated logging operations for sawlogs and chipwood commenced in 1975. The history of logging in the region has been reviewed more fully by Collins and Barrett (1980), Bradshaw and Lush (1981) and Borg *et al* (1987). Current silvicultural practices are described by Bradshaw (1985, 1986).

Table 1 lists sawlog and chipwood production from the Woodchip Licence Area since 1975 and Figure 3 shows the distribution of cut-over areas. In 1977 the Forests Department introduced the concept of multiple use into its forest management (Forests Department, 1977). Under this concept, land is managed to simultaneously provide for as many different uses or purposes as possible. Incompatibility between uses is overcome by ranking according to priority as follows: priority use, compatible use, conditional use, incompatible use. With the restructuring of the Forests Department into the Department of Conservation and Land Management (CALM) in 1983, the multiple use concept was retained (CALM, 1987).

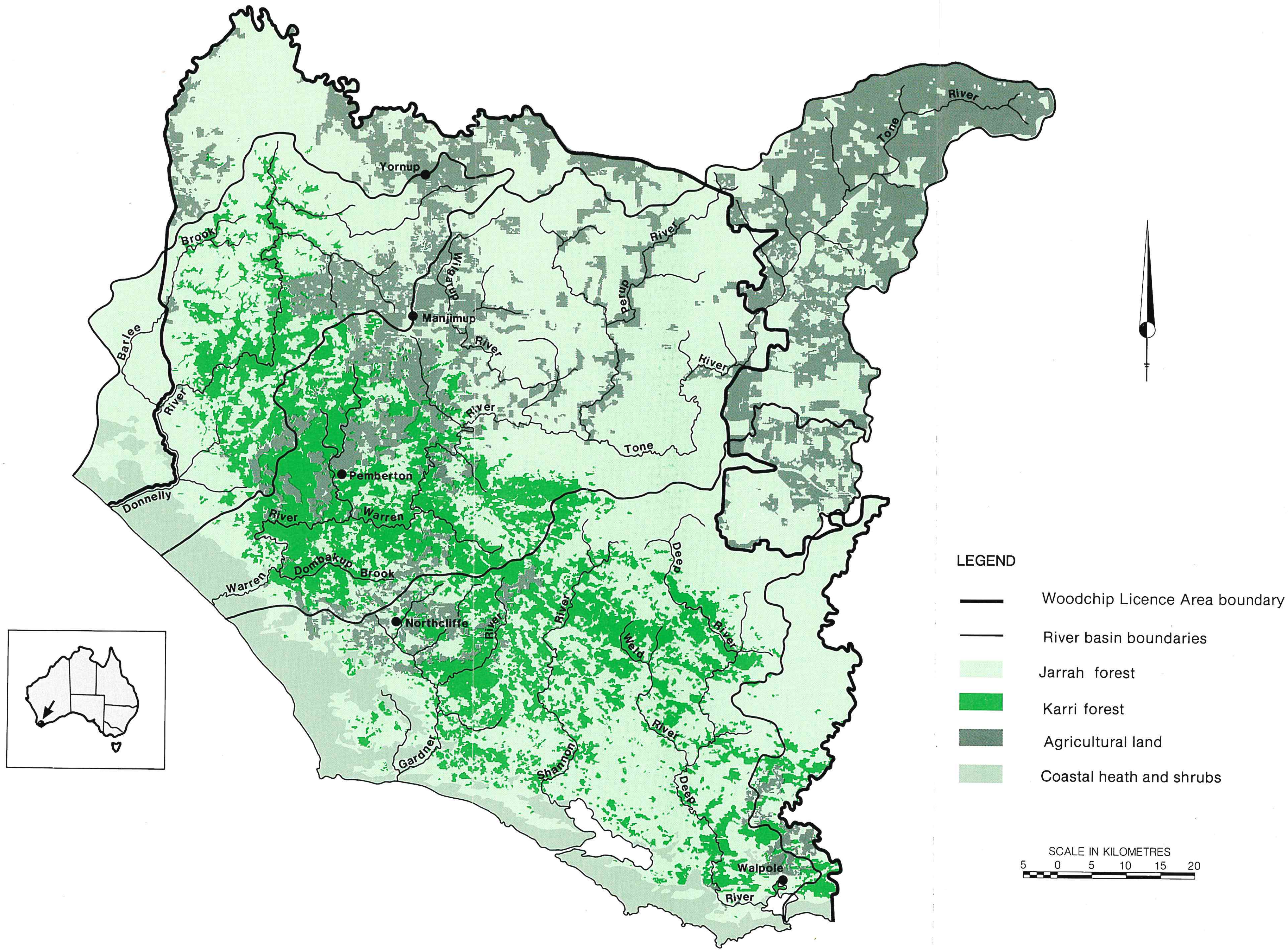

Figure 1
The Woodchip Licence Area in the southern forest of Western Australia. (Map based on data from the FMIS data base of the Department of Conservation and Land Management W.A., and Smith 1972.)

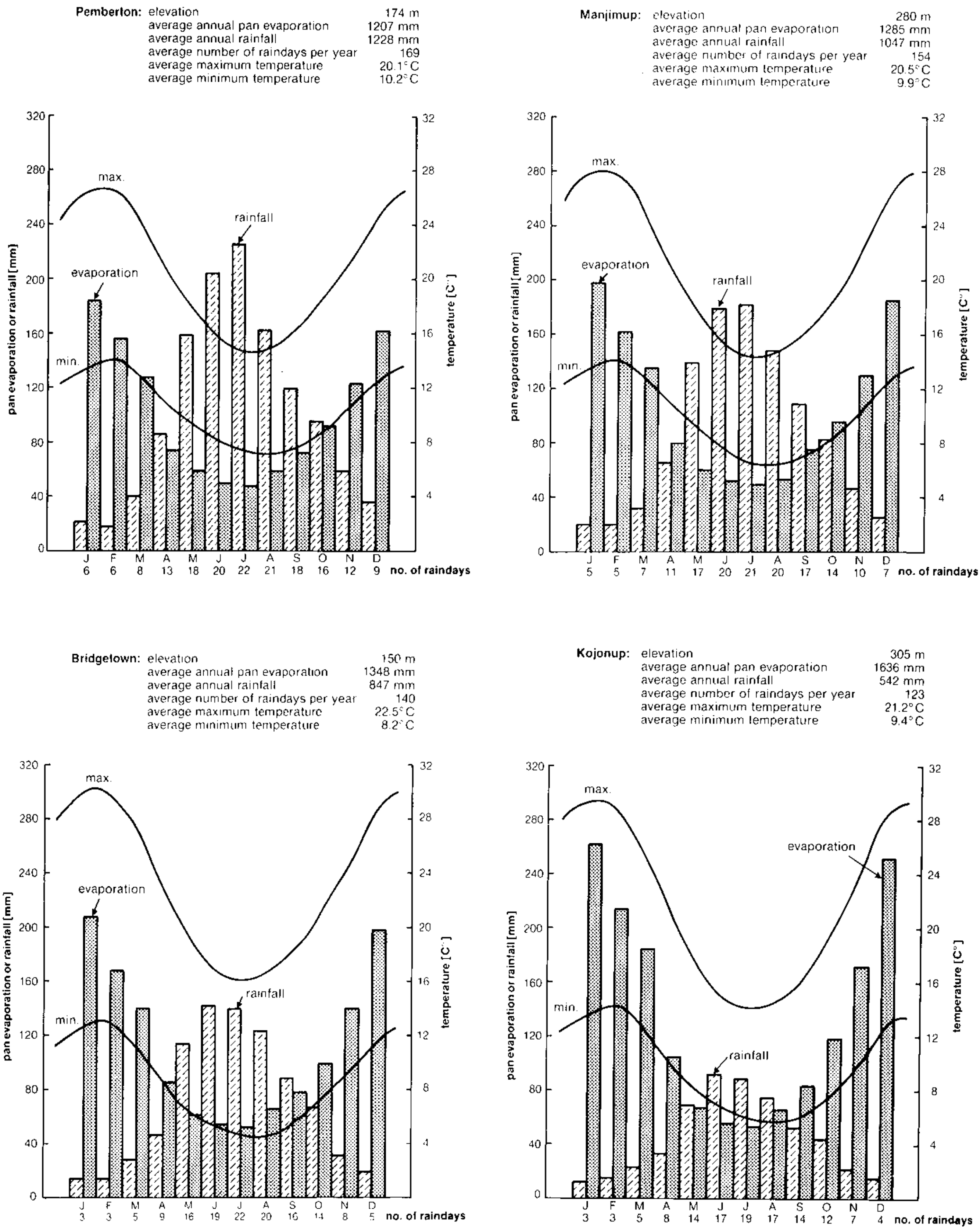

Figure 2
Seasonal patterns of rainfall, pan evaporation and temperature

Water Resources

The southern forest region contains most of the Donnelly, Warren and Shannon River Basins (Figure 1). They generate an average annual streamflow of 1550 x $10^6 m^3$ of which 720 x $10^6 m^3$ are readily divertible (Collins and Barrett, 1980). This represents 39% of all surface water resources and 27% of the combined surface and groundwater resources in south-west Western Australia.

Less than 1% of these resources are currently used for public water supplies. However some 23% of the total south-west resources are developed (Western Australian Water Resources Council, 1984) and overall demand is growing rapidly. The untapped resources of the Shannon, Warren and Donnelly River Basins are therefore of major regional significance in the long term and ensuring their quality in the future is of high priority. In the short to medium term, relatively small-scale water resource projects (which yield less than a few million cubic metres per annum) are likely to be developed to meet local demand.

Already, as a result of agricultural development, some 245x$10^6 m^3$ or 34% of the divertible surface water resources of the Donnelly, Warren and Shannon River Basins are no longer fresh. The Warren River is the major resource affected and is now classified as being of marginal salinity, i.e. in the range 500 to 1000 mg/L Total Soluble Salts. The introduction of controls over large-scale agricultural development, through the Country Areas Water Supply Act (1947-76) in 1978, was a major step in protecting the Warren River from further salinity deterioration.

State forest areas provide the majority of the fresh water resources of the region and are particularly important in diluting the saline flows draining agricultural areas with average rainfalls less than about 1000 mm per year. Continued management of the forests to provide high quality water is critical and is a corner-stone of regional water resource management policy (Sadler and Williams, 1981).

Hydrological Characteristics

Borg *et al*, (1987) provide a detailed hydrologic background of the area and place specific emphasis on hydrologic processes likely to be affected by forest logging activities. Martin (1987) has given details of the groundwater characteristics and their hydrogeological setting. The interested reader is referred to other recent reviews for further background (Steering Committee for Research on Land Use and Water Supply, 1984; Western Australian Water Resources Council, 1986). Only a simplified picture of regional hydrologic characteristics is given here.

Streamflow generation

The sources of streamflow are overland flow, throughflow and groundwater flow. The soil characteristics of the study region favour throughflow as the major source of streamflow. The soils generally comprise highly permeable sandy to loamy A horizons overlying low permeability clays at 30-100 cm depth (McArthur and Clifton, 1975). During winter, rainfall infiltrates the soil surface, perches on the clay B horizon and flows downslope to discharge to streams. Over 90% of streamflow may be generated by this shallow throughflow (Stokes and Loh, 1982). However, on an average annual basis, only 25% of rainfall in the high rainfall zone becomes streamflow, and in the low rainfall zone this value is as low as 5% of rainfall. Only a very small portion of rainfall recharges groundwater and most of the rainfall is evapotranspired back to the atmosphere. A significant proportion of winter rainfall can be stored in the soil and transpired during spring and summer.

Overland flow is usually restricted to low landscape positions which become saturated. According to Stokes and Loh (1982), these 'variable source areas' contribute only about 5% of annual flow, but are responsible for generating peak flood flows.

Groundwater and salt discharge

Groundwater is conveniently described by two systems, the perched aquifer and the deeper or permanent aquifer. The perched aquifer is ephemeral and, where it does not intersect the permanent groundwater, is fresh. Where a saline permanent groundwater has contributed to the perched aquifer, shallow throughflow may carry substantial amounts of salt to the stream.

The permanent groundwater system in the high rainfall zone (annual rainfall greater than 1100 mm) usually discharges to streams and keeps these areas leached of salt. As such, the high rainfall zone is generally of low salinity hazard. In the low rainfall zone, the deep groundwater tables are at considerable depths below the stream bed and do not contribute to streamflow. As a consequence, salt has accumulated in the unsaturated zone and these areas pose a high potential salinity hazard. However the large depth of unsaturated zone means that only persistent forest changes which increase recharge over long time periods (tens of years) are likely to cause stream salinity problems. This has occurred in the case

Table 1

Timber volumes extracted from Crown Land in the Woodchip Licence Area between 1976 and 1985

Year	Area cut-over (ha)					Sawlogs (m^3)			Chipwood (m^3)				
	jarrah		karri		karri regrowth								
	total[1]	chipped[2]	total[1]	chipped[2]	thinned	jarrah	marri	karri	jarrah	marri	karri	thinnings	total
1976	6470	-	3520	1850	-	148000	3400	300500	-	169000	103000	-	272000
1977	5880	140	2050	2690	-	156800	8400	264000	-	313600	111000	-	424000
1978	4550	320	2660	3220	-	160300	9800	280700	-	317200	100400	-	417600
1979	2760	1160	2280	2580	-	138300	10200	269500	-	414800	92000	-	506800
1980	3440	2120	2040	2310	140	177100	8200	260900	4900	444300	125000	11500	585700
1981	4120	1450	1450	1580	250	182500	8200	239500	-	308700	100300	22900	431900
1982	4220	820	1220	1330	260	167600	7600	206300	-	263800	78500	22500	364800
1983	3200	890	1730	1520	270	108600	6700	201700	-	273200	101600	25000	399800
1984	3150	2100	2120	2500	390	117000	10900	250600	-	382000	74100	25300	481400
1985	4560	2640	1530	1610	320	229200	16100	222600	-	417400	68000	27300	512700

[1] area logged for sawlogs with or without subsequent removal of chipwood.

[2] area from which chipwood was removed after sawlog extraction; for karri this includes areas cut-over for sawlogs prior to the opening of the chipmill where chipwood was left standing for later removal; the area chipped is therefore often greater than the area cut for sawlogs.

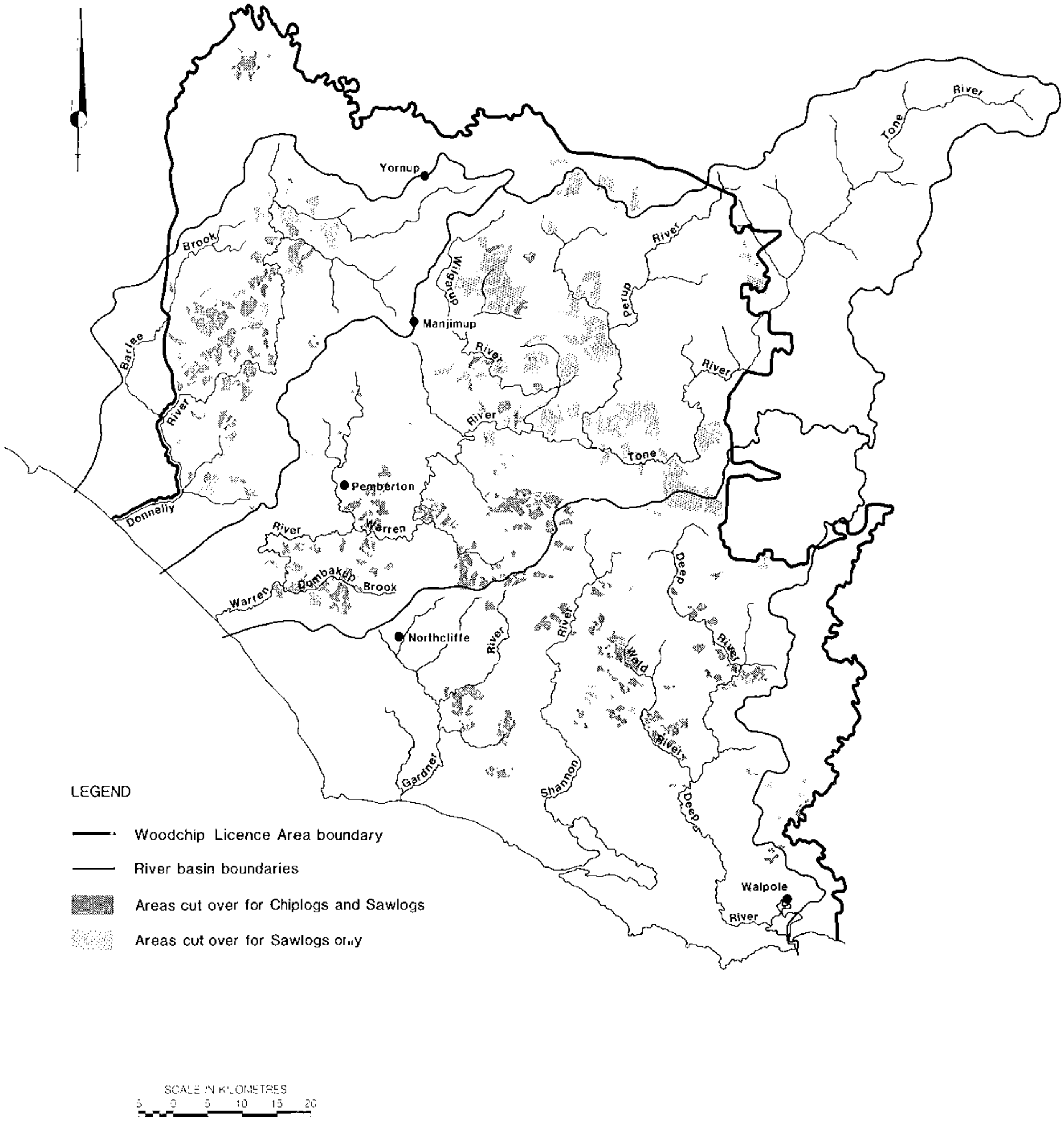

Figure 3
Areas cut-over since 1975

of agricultural development.

The intermediate rainfall zone often poses the major problem to partial or transient land use changes because the permanent groundwater is of moderate salinity and the water table depths below streams are frequently small.

Stream salinity characteristics

Stream salinity is governed by the relative volumes and salinities of overland flow, shallow throughflow and groundwater flow. As described above, permanent groundwater is the major source of salts, and throughflow and overland flow tend to dilute this source.

Annual mean stream salinities of forest catchments range from 80 to 400 mg/L Total Soluble Salts (TSS). The lowest stream salinities (~100 mg/L TSS) occur in the low rainfall zone where groundwater does not discharge to streams. In the high rainfall zone, where discharging groundwater salinities are low, stream salinities are again low (~150 mg/L TSS). Streams which drain the intermediate rainfall zone have the highest salinities in all forest areas. Annual average values are commonly about 250 mg/L (Loh *et al*, 1983) but can approach 400 mg/L TSS in some cases. These high salinities result from a discharging groundwater of moderate salinity and limited throughflow of low salinity.

Stream salinity can also show strong seasonal and annual variations. In a seasonal context, the variability is usually associated with the proportion of throughflow, which is high in mid-winter and low in spring and autumn. Annual variability may be attributed to annual variation in throughflow due to rainfall variation, and to longer term changes in groundwater level resulting in greater or smaller contributions of groundwater to streamflow.

Stream Sediment Concentrations

Stream sediment concentrations of undisturbed forest are generally below the level of reliable detection (5 mg/L suspended solids less than 63 microns in size). The highly permeable soils and related lack of surface runoff, the generally low relief, and the high litter and understorey vegetation all contribute to very low sediment loads. Organic material from the natural decay of vegetation and disturbances due to logs naturally falling into stream channels have been the major source of suspended material measured in undisturbed catchments.

3. *Research Objectives and Programme*

Research Objectives

At the outset of the research programme, the Steering Committee established four projects to address both short-term and long-term effects of the proposed logging operations. These projects were:

Project 1: Identify areas vulnerable to salinity increases.

Project 2: Carry out a well controlled experiment to study the changes in surface and groundwater hydrology through the complete regeneration cycle.

Project 3: Monitor the major rivers of the region to identify any large-scale changes in water quality.

Project 4: Monitor the groundwater and streamflow response in operational coupes (a single unit of logging and regeneration) to provide an early warning of any major environmental problems in the early years of the new cutting regimes.

Previous reports (Steering Committee for Research on the Woodchip Industry, 1978, 1980) have provided interim results and conclusions from these projects separately. In this review the research results have been integrated in line with the development of the research programme. The general objectives are to:

(i) determine the magnitude and duration of any increase in stream salinity resulting from the logging operations;

(ii) determine the magnitude and duration of any increase in stream sediment concentration resulting from the logging operations;

(iii) determine the long term (20 to 100 years) effect of the logging and regeneration on catchment water yields;

(iv) propose, if necessary, improved logging practices to preserve water quality.

Specific Concerns Within the Manjimup Woodchip Licence Area

Of particular interest was the north-eastern low rainfall sector of the Manjimup Woodchip Licence Area (annual rainfall < 900 mm/year) where clearing for agriculture has caused large and persistent increases in stream salinity. Light selection cutting had been practiced there for many decades without any observed effects on stream salinity. However, because of the high soil salinities associated with the low rainfall, there was some concern that a heavier cutting regime could lead to a serious stream salinity problem (Forests Department, 1973). Logging in this area (Coonan, Yardup and Warrup Blocks) was therefore restricted to the selective removal of sawlogs. Marri chiplogs were not to be extracted, except for experimental purposes, in the first ten years of the woodchip operation. Consequently, the research programme has specifically addressed the effect on stream salinity of intensive cutting in the low rainfall zone.

In the intermediate rainfall zone (900-1100 mm/year), clearfelling had been carried out previously without apparently affecting stream water quality. For this reason it was considered safe to allow clearfelling and heavy selection cutting in this rainfall zone. However, measurable salinity deterioration followed agricultural development in some areas of the intermediate rainfall zone (Department of Agriculture, 1974). Monitoring and research in this zone were therefore given high priority to provide more reliable hydrologic information to guide forest management.

Possible reduction in water yield from converting substantial proportions of the southern forest to young vigorous regrowth forests has become a concern due to increasing demand for potable water. Large differences between water yields from unthinned regrowth and virgin forests in Victoria (Brookes, 1950; Brookes and Turner, 1963) have highlighted this issue. The research programme will enable long-term trends in water yields in relation to forest density to be determined.

Research Programme

The specific research programme of the original Kelsall Committee is described below.

Project 1: The identification of areas vulnerable to salinity increase was carried out by an extensive drilling programme for soil salt storage (Johnston *et al*, 1980) and regional stream salinity sampling (Department of Agriculture, 1974). More intensive sampling was carried out in the intermediate rainfall zone (Steering Committee for Research on the Woodchip Industry, 1980) and the results were correlated with land use and other catchment characteristics.

Project 2: A detailed paired-catchment experiment was established to provide accurate information on changes in both surface and groundwater hydrology as

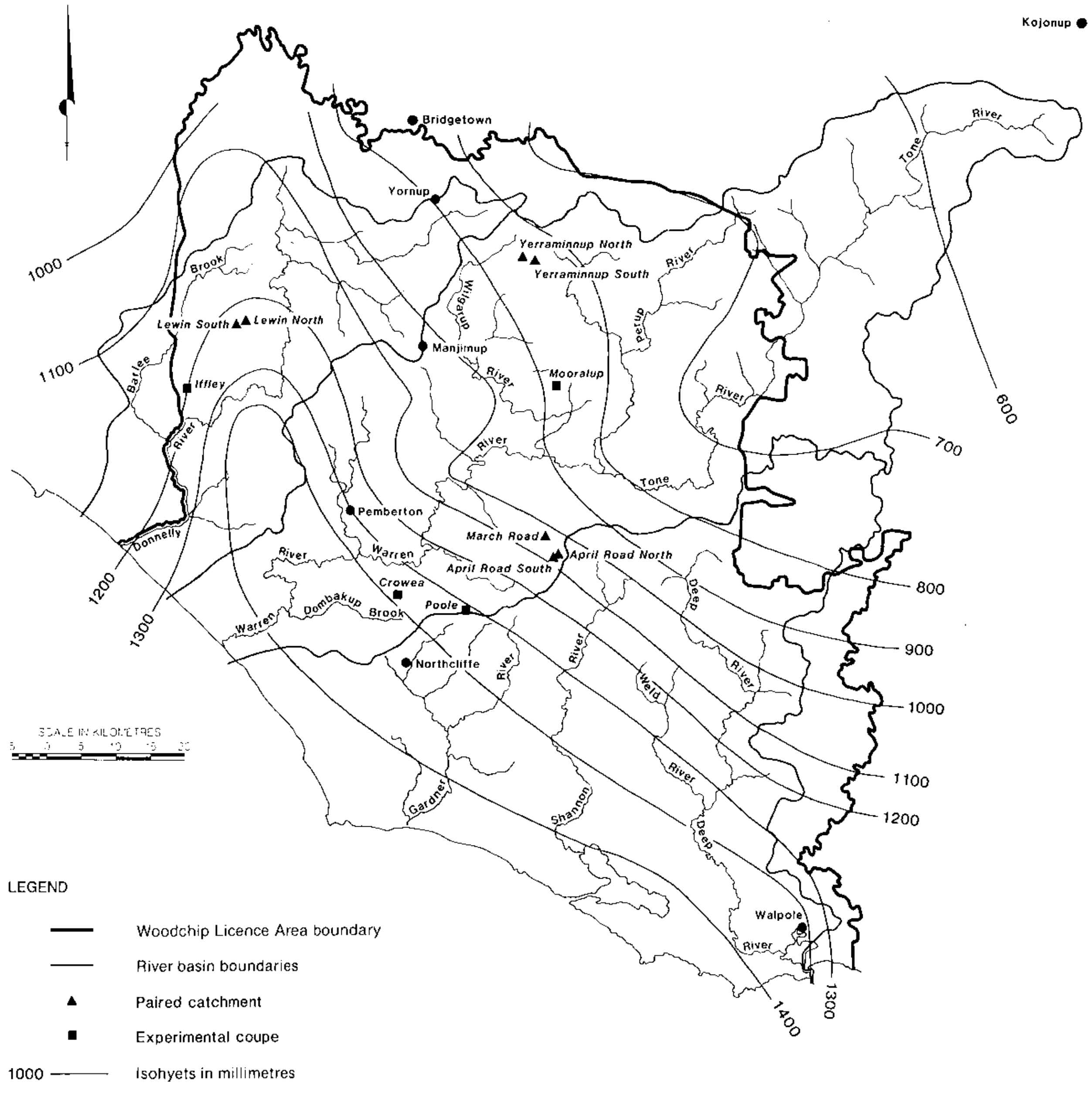

Figure 4
Location of paired catchments and experimental coupes

a result of the proposed logging operations. Seven experimental catchments in three groups covering the range of forest types across the intermediate and low rainfall zones were established (Figure 4). Following a period of pre-treatment calibration, one catchment in each group was left as a control and the others logged and regenerated in accordance with the current range of forest management practices. In this way, changes in streamflow volumes, salinities and sediment loads caused by the catchment treatment could be identified, independent of their large natural variations. In addition, approximately 10 to 12 groundwater bores on each catchment were established to identify the response of the groundwater system to the catchment treatment. Logging commenced in 1982 and most logging and regeneration operations were completed by the winter of 1983. Post-treatment results from three years of monitoring are therefore available.

Project 3: The monitoring of major rivers in the region to identify any large-scale changes in water quality due to logging was integrated with the State Water Resources Assessment Programme. Daily sampling for sediment and salinity concentrations was carried out at 12 gauging stations with varying proportions of forest and agricultural development.

Project 4: Four operational coupes, selected as experimental catchments, were monitored for one year prior to logging in 1977 (Figure 4). While monitoring was not as thorough as in the paired-catchment project, and pre-treatment calibration was very limited, the nine years of post-treatment data now available from these coupes have provided very useful information, particularly on the longer term groundwater responses to logging.

Results from Projects 1 and 3 have been previously reviewed (Steering Committee for Research on the Woodchip Industry, 1980). This review places emphasis on results from the experimental paired catchments and monitored operational coupes of Projects 2 and 4.

Although initially focused on the individual projects described above, the research has become integrated over time. The understanding of the hydrology of the region has drawn heavily on related research projects studying the effect of agricultural development and bauxite mining and on information collected under the State Water Resources Assessment Programme.

Catchment Treatments

Table 2 summarises details of the coupes and catchments studied.

The experimental coupes cover the full range of forest types and rainfall zones being cut over in the first ten years of operation of the woodchip project (Figure 4). Mooralup coupe is located on the western edge of the low rainfall zone and was selected as the most appropriate coupe to represent similar jarrah-marri forest to the north-east.

The paired catchments represent the range of forest types in the intermediate and low rainfall zones. The Yerraminnup catchments were located within the area excluded from operations within the first 10 years of the programme. Chiplog removal from Yerraminnup catchment was carried out only for the purpose of the experiment.

Details of all treatments are summarised in Table 3. The predominantly karri stands were clearfelled and replanted with karri. The jarrah-marri stands had a heavy selection cut in which sawlogs and chiplogs were removed but groups of trees with potential to grow into good quality timber were retained. The basal area and estimated leaf cover retained are also documented in Table 3.

Under the original Environmental Impact Statement (Forests Department, 1973), 200 metre wide stream reserves (100 metres each side of the stream) of approximately 2 kilometres length per 5 square kilometres of area were to be established primarily to provide a refuge and corridor linking system for fauna. This implied that about one in three first and second order streams were planned to have a stream reserve. These were identified on maps associated with the management plan. Logging operations could proceed all year round so long as strict conditions to prevent soil disturbance were not exceeded.

Under current practice some coupes are logged through winter while others are only logged through summer. Consequently, individual streams are exposed to a varying degree of risk of salinisation and sedimentation, ranging from cases where stream reserves are left and summer logging takes place, to cases where winter cutting takes place with no stream reserve protection.

Table 2
Characteristics of Experimental Catchments

Catchment Name	Soil Type	Forest Type	Mean Rainfall (mm) Long Term	Mean Rainfall (mm) For Study Period	Area (ha)
PROJECT 4					
Crowea	red and yellow duplex soils	mainly karri-marri some jarrah-marri	1380	1101	114
Poole	mostly yellow duplex soils, some laterite and colluvium	mainly karri-marri some jarrah-marri	1310	1069	121
Iffley	various kinds of duplex soils, some gravelly loam associated with laterite	jarrah-marri	1200	861	175
Mooralup	red and yellow duplex soils, some colluvium and sand	jarrah-marri	880	698	112
PROJECT 2					
Lewin North	laterites yellow podzolics red earths	jarrah-marri and karri	1240	1102	133
Lewin South			1230	1098	90
March Road East	laterites yellow podzolics red earths	marri-karri and karri	1040	973	261
April Road North	laterites upland swamps yellow podzolics	jarrah-marri some karri on slopes	1070	995	248
April Road South	laterites yellow podzolics	jarrah marri-karri	1080	1011	179
Yerraminnup North	laterites and yellow podzolics	jarrah-marri	850	760	253
Yerraminnup South			830	746	183

Table 3
Treatments applied to experimental catchments

Catchment/Coupe Name & Number	Logging Operation Description	Volumes of Logs Removed — m³	Logging Period	Stream Buffer Retained	Vegetation Retained: Basal Area m²/ha	Vegetation Retained: %Crown Cover	Regeneration/Silvicultural Treatment: Method	Regeneration/Silvicultural Treatment: Regeneration Burns
PROJECT 4 COUPES								
CROWEA 12	Predominantly Clearfelled	Karri Sawlog - 11500 Jarrah Sawlog - 670 Chipwood - 16980	Jan 77 to Feb 78	No	Nil(K) ~11(J)	Nil(K) ~15(J)	Karri — hand planted Jarrah/marri — natural regeneration	April 78
POOLE 9	Predominantly Clearfelled	Karri Sawlog - 10800 Jarrah Sawlog - 3760 Chipwood - 16980	Jan 77 to Mar 78	No	Nil(K) ~11(J)	Nil(K) ~15(J)	Karri — hand planted Jarrah/marri — natural regeneration	April 78
IFFLEY 9	Heavy selection cut	Karri Sawlog - nil Jarrah Sawlog - 5380 Chipwood - 11100	Nov 76 to Feb 78	No	11.4	15.1	Natural regeneration	Nov 79
MOORALUP 2	Heavy selection cut	Karri Sawlog - nil Jarrah Sawlog - 3450 Chipwood - 7560	Nov 76 to Feb 78	No	10.6	14.2	Natural regeneration	Nov 79
PROJECT 2 CATCHMENTS								
MARCH ROAD (Sutton 13)	Clearfelled	Karri Sawlog - 18772 Jarrah Sawlog - 8448 Chipwood - 47436	Jan 82 to Mar 83	No	Nil	Nil	Karri — hand planted	March 83
APRIL ROAD NORTH (Sutton 19/21)	Clearfelled	Karri Sawlog - 9703 Jarrah Sawlog - 6776 Chipwood - 29410	Jan 82* to Mar 83	Yes	Nil	Nil	Karri — hand planted	March 83
LEWIN SOUTH (Lewin 4)	Heavy selection cut in J/M, karri gully clearfelled	Karri Sawlog - 330 Jarrah Sawlog - 3610 Chipwood - 6700	Jun 82 to Dec 82	No	7	11	Cull treatment Jun 83 to Sept 83 karri — hand planted J/M — natural regeneration	Feb 84(K) Nov 83(J)
YERRAMINNUP SOUTH	Heavy selection cut	Karri Sawlog - nil Jarrah Sawlog - 2740 Chipwood - 4380	Jan 82* to Apr 83	Yes	5	10	Cull treatment Jun 83 to Dec 83 J/M — natural regeneration	Oct 83

Note: (K) denotes karri and karri-marri stands
(J) denotes jarrah and jarrah/marri stands
(*) Logging during this period was restricted to dry summer conditions only

The two Sutton block catchments provided an opportunity to evaluate the different hydrologic effects of this range of current forest management practices. March Road catchment was clearfelled through the winter so long as soil conditions allowed. In the April Road North catchment the forest was retained for 100 metres on either side of the main streamline and the rest clearfelled during the dry months. No stream reserves were left on any of the experimental coupes of Project 4.

Both March Road and April Road North were larger than the normal maximum clearfelled coupe size of 200 hectares. For the purpose of the hydrologic experiment it was necessary to treat the complete catchment. The catchments therefore pose a slightly larger risk of sediment and erosion than would be the case operationally in the intermediate rainfall zone.

On Yerraminnup South catchment, the most desirable silvicultural treatment appropriate to chipwood removal from the low rainfall zone was carried out. This involved all sawlog and chiplog material being removed and an additional non-commercial culling treatment to remove all unwanted competition from the regenerating forest. The retained basal area and leaf cover were only 5 square metres per hectare and 11% respectively. The amount of retained forest cover in this type of operation is variable from one coupe to the next, but generally not as low as Yerraminnup South. A 50 metre stream buffer was left on either side of drainage lines to minimise the possible impact of the logging on both salinity and sediment concentrations.

4. Research Results

Details of the research results are provided in technical reports on the experimental coupe responses (Project 4) (Borg *et al*, 1987), the groundwater responses of the paired catchments (Project 2) (Martin, 1987) and the catchment responses of the paired experimental catchments (Project 2) (Borg and Loh, 1987). Stoneman *et al*, (1987) have detailed the response of regrowth following logging and clearfelling at the research sites and other older stands throughout the region. A summary of the overall results is provided here.

Rainfall

During the period 1975 to 1985 inclusive, the annual rainfall was on the average 10% below the long-term mean. This is based on the records from nine long term raingauges located across the study region (Borg *et al*, 1987) and rainfall records for the paired catchment sites.

Rainfalls recorded at the experimental coupe sites were about 20% below the long term mean. However, these were non-standard raingauges and the raingauge catch was thought to be low. Rainfall figures at the experimental catchments are given in Table 2.

Forest Regeneration

In all rainfall zones the vegetation recovered quickly after logging. Vegetation cover approached pre-logging levels within 5 to 10 years after logging in karri stands. Jarrah-marri stands responded more slowly, reaching 90% of pre-logging cover in about 10 to 15 years and 100% of pre-logging levels in 20 to 50 years (Figure 5). Based on regrowth stands of older age karri, there is evidence that higher densities than the original forest develop after about 15 to 20 years and, without subsequent thinning, persist for about 100 years.

Groundwater Responses

Coupe studies

In all rainfall zones, groundwater levels in the experimental coupes rose for 2 to 4 years following logging and then began to decline as the regeneration developed. In the longest available records, groundwaters are still higher 8 years after logging than prior to logging but are continuing to decline. This is shown in Figure 6, in which groundwater levels relative to control bores have been plotted for the Poole and Crowea coupes. At the current rate of groundwater decline, and ignoring climatic variations, it would take about 13 years following commencement of regeneration for permanent groundwaters to return to the level they would have been without logging.

Paired catchment studies

Figure 7 shows the groundwater changes on treated paired-catchments relative to the controls. While only 3 years post-regeneration data are available, permanent groundwaters are close to their peak or declining slightly in Lewin South and Yerraminnup South catchments. Groundwaters on March and April Road North catchments have yet to reach their peak, although this may well have occurred in bores located in the stream zone of the March Road catchment. Where groundwaters are still rising, their rate of rise is decreasing and groundwater levels appear to be near their peaks. If responses are similar to the experimental coupes, groundwaters can be expected to decline in the next year or two.

Figure 8 shows monthly observations at one valley site on March Road catchment. Measurements from bore 205 show that, prior to clearfelling, the permanent groundwater level oscillated between 3 and 5 metres below ground surface and rose to within one metre of the surface following clearfelling. Comparison with bore 218, which was installed in 1981 prior to treatment, shows that a vertical upward head gradient has existed (at least since 1983) at the site, indicating that permanent groundwater could potentially contribute to the nearby stream. Bore 219 shows the typical seasonal behaviour of the perched aquifer which becomes saturated during winter and dries out in summer.

Groundwater responses on side slopes were compared with groundwater responses along valleys to evaluate any effect of the vegetation retained in stream reserves. The response of stream bores in April Road North (with buffer) has been much smaller and more delayed than March Road (no buffer) (Figure 7). Comparison of slope and streamline bores on Yerraminnup South catchment indicated similar responses until 1984 when groundwaters began to recede in the stream zone where a buffer strip was maintained. However not all these observed differences can be attributed to the difference in retained streamline vegetation. This is particularly the case in the Sutton Block catchments. Because of some localised features of the groundwater

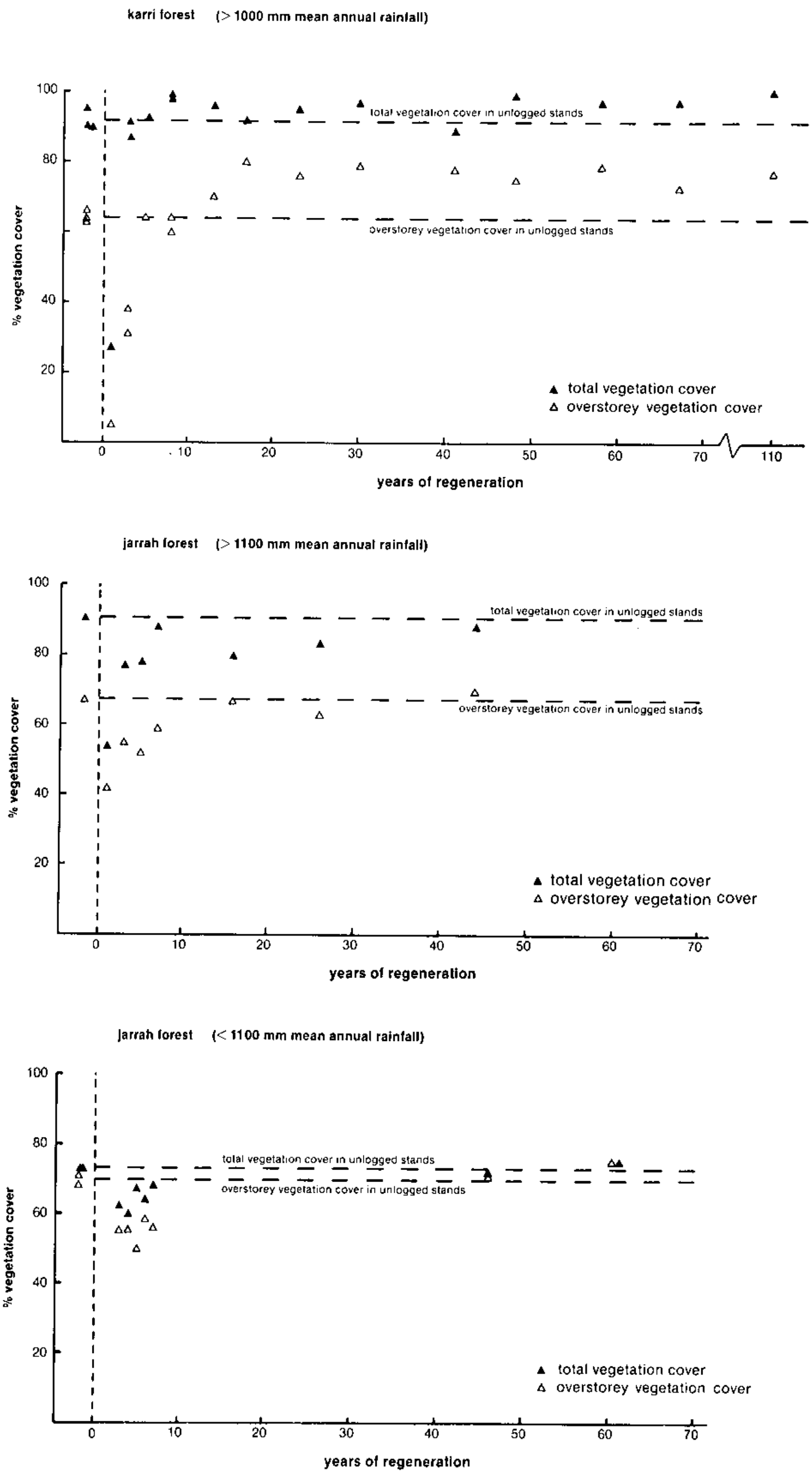

Figure 5
Regeneration of forest cover after logging

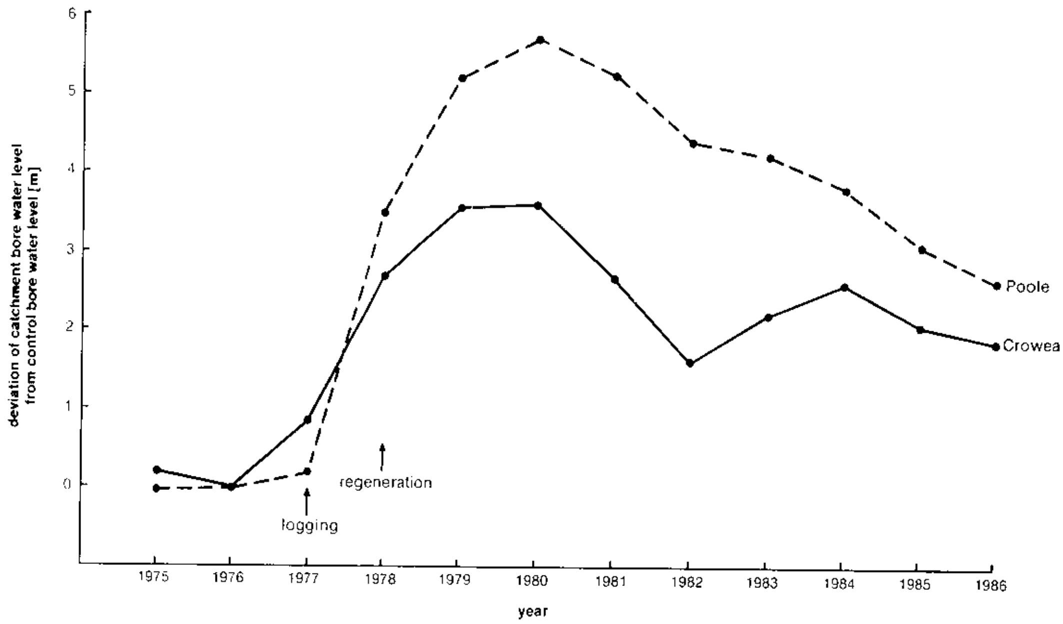

Figure 6
Change in minimum groundwater level relative to control bores following logging in two experimental coupes

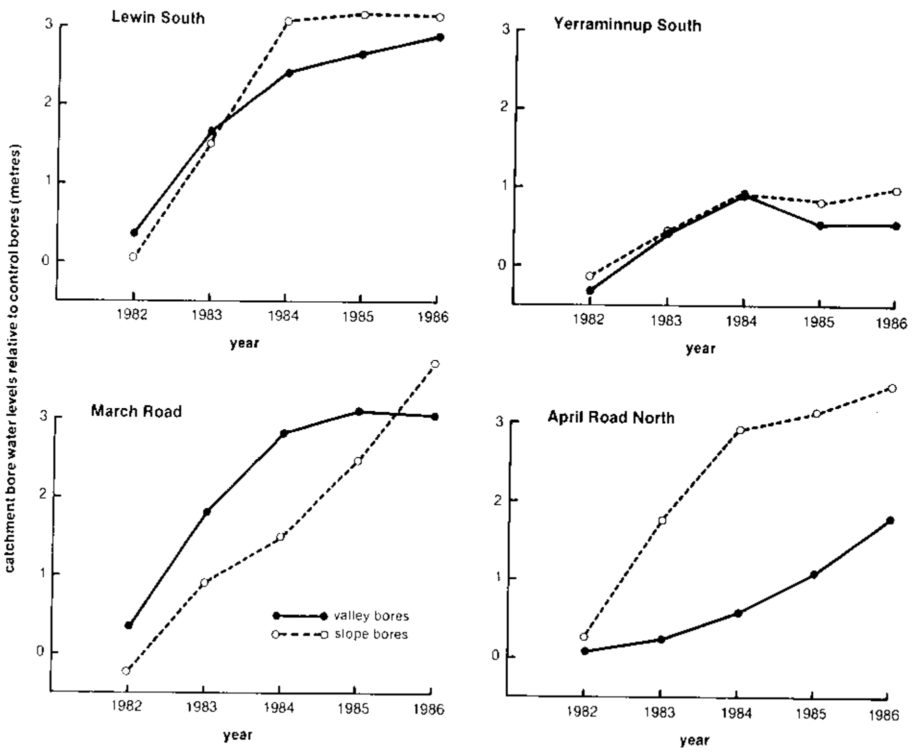

Figure 7
Changes in treated catchment bore water levels relative to control bores since logging

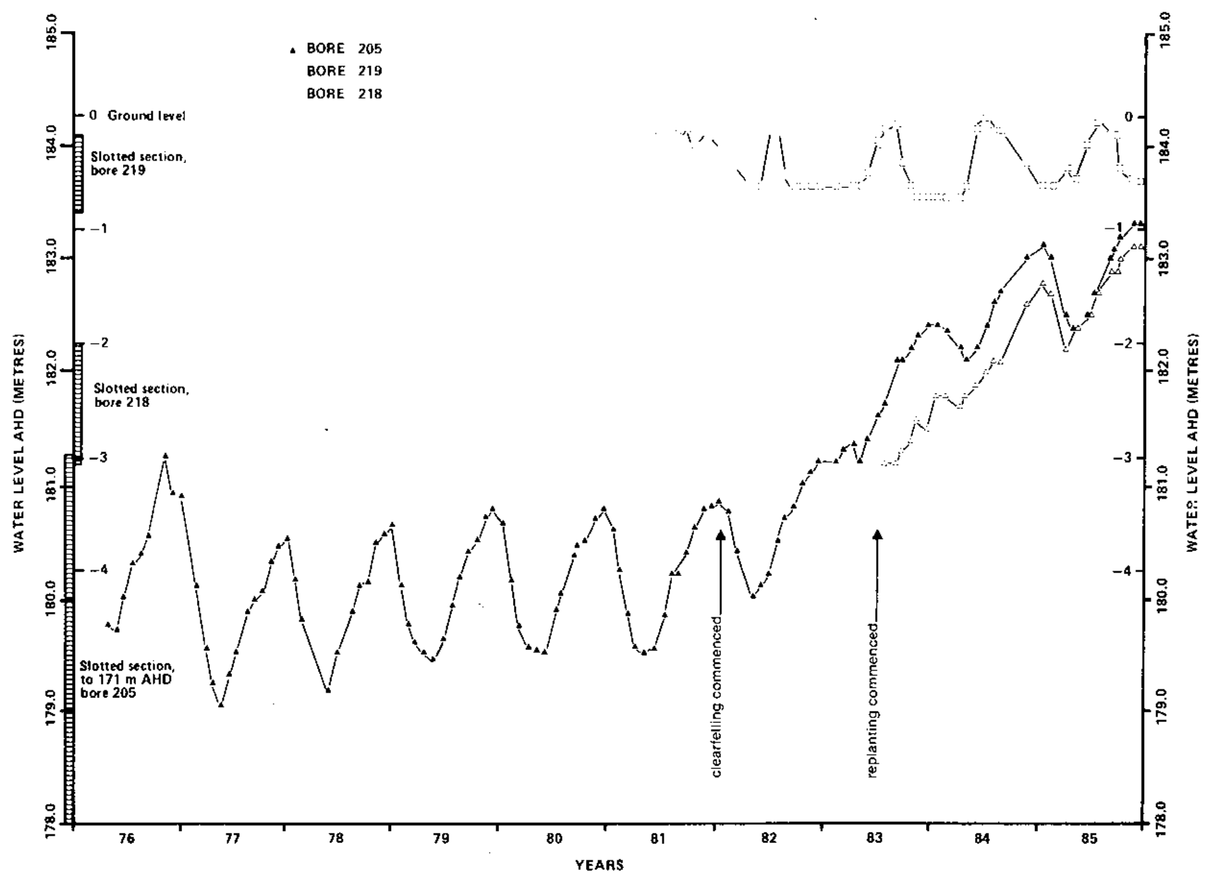

Figure 8
Groundwater responses at a valley site in the March Road catchment

system, the bore water levels prior to logging in the lower valley areas at April Road North were about 8 metres below the surface in contrast with only 2 metres below the surface on March Road catchment (Martin, 1987).

Stream Salinity

Table 4 summarises the changes in annual flow-weighted stream salinity concentration for the eight treated catchments studied. Maximum annual flow-weighted stream salinities occurred on the experimental coupes in 1979, two years after the commencement of regeneration. Salinities had declined significantly by 1986, a similar low-rainfall year. Salinities on the paired catchments reached a maximum in 1985 (most recent data) two years after the commencement of regeneration.

In the low rainfall zone, groundwater did not contribute to streamflow prior to logging. The rise in groundwater levels after logging was not sufficient to generate any groundwater contribution to streamflow. Stream salinity therefore did not rise (Mooralup and Yerraminnup South, Table 4). In fact, there was a slight temporary decrease in annual stream salinity due to some increase in surface runoff and shallow throughflow.

In the intermediate and high rainfall zones, groundwater contributed to streamflow prior to logging. Concurrent with the rise in groundwater levels, there was a rise in annual flow-weighted stream salinity of 50 to 150 mg/L TSS, indicating that the proportion of streamflow contributed by groundwater was increasing (Table 4). Concurrent with the subsequent decline in groundwater levels, stream salinity declined.

In all monitored catchments, independent of rainfall zone, the mean annual stream salinity was less than 500 mg/L TSS prior to logging. At their highest level, 2 to 4 years after logging, stream salinities were still well below 500 mg/L

Table 4
Annual flow-weighted salinities of streams draining experimental catchments before and after logging

Coupe/ Catchment	Mean Annual Rainfall (mm)	Year of Logging	Mean TSS Before Logging (mg/L)	Maximum TSS After Logging (mg/L)	TSS in 1985 (mg/L)
PROJECT 4					
Crowea	1380	1977	142	192 (1979)	153
Poole	1310	1977	102	196 (1979)	163
Iffley	1200	1977	352	432 (1979)	307
Mooralup	880	1977	no data	142 (1980)	no flow
PROJECT 2					
Lewin South	1220	1982	99	182 (1985)	182
March Road	1070	1982	153	314 (1985)	314
April Road North	1070	1982	101	140 (1985)	111
Yerraminnup South	850	1982	133	114 (1985)	114

Notes (1)

Values are the Toal Soluble Salts (TSS) concentration determined as the sum of major ions dissolved in the water sample. The annual flow weighted mean is effectively the concentration derived by the annual mass of solute discharged via the stream is divided by the annual volume of water discharged via the stream.

TSS (Table 4). A greater length of record will be required to determine how closely stream salinities return to pre-logging levels.

The largest increase in annual stream salinity (about 150 mg/L) occurred on March Road catchment, an intermediate rainfall zone catchment which was clearfelled and did not have a stream buffer. Low-flow stream salinities of this catchment increased from a maximum of 700 mg/L before logging to more than 1500 mg/L after logging. The stream salinity remained above 1500 mg/L for about four weeks following the commencement of streamflow in the third year after logging. In the same year the stream salinity remained above 1000 mg/L for six weeks following the commencement of streamflow and for one week prior to the cessation of streamflow. The stream discharges for these periods when stream salinities exceeded 1500 mg/L and 1000 mg/L comprised only 1.1% and 3.3% respectively of the annual streamflow volume.

Stream Sediment Concentrations

Prior to logging, the mean annual stream sediment concentrations were less than 5 mg/L in all monitored catchments, independent of rainfall zone. Sediment concentrations increased in two of the four paired catchments and remained elevated for one to two years following logging, but then declined rapidly to pre-logging levels over the next two to three years (Figure 9). The catchments where measurable increases in sediment concentrations occurred had no buffer of streamside vegetation retained and were logged through both summer and winter periods. The highest annual flow weighted sediment concentrations were 38 mg/L on March Road catchment and 20 mg/L on Lewin South catchment. The highest values occurred in the winter where the least vegetation cover existed in the stream and lower slope areas, that is, following the karri regeneration burn. Stream sediment concentrations can be expected to return to pre-logging levels within 4 to 5 years after logging (Figure 9).

Where stream buffers were retained and logging restricted to dry summer conditions, no increase in stream sediment concentration was detected after logging (Figure 9). The independent effects of summer logging and stream reserves cannot be isolated with the research information currently available. Nevertheless, it is clear that with both summer logging and stream buffers no measurable increase in sediment load was detected (April Road North).

Water Yield Changes

In all rainfall zones streamflow increased for 2 to 3 years after logging and then gradually declined. Results from the paired-catchment studies indicate that increases in excess of 100 mm/year, about double the pre-treatment streamflow, occurred on the Lewin and Sutton catchments in the first two years following treatment. Increases of less than 40 mm/year occurred in the low rainfall Yerraminnup South catchment although this still represented a yield increase of over 100% in the second year following treatment. Virtually all the increased streamflow came from additional shallow throughflow. Results from the experimental coupes (Figure 10) suggest that about 12 years after regeneration commences, the annual streamflow volumes may be back to their pre-logging levels. In the Mooralup catchment, where streamflow volumes were small initially, this may have occurred in seven years.

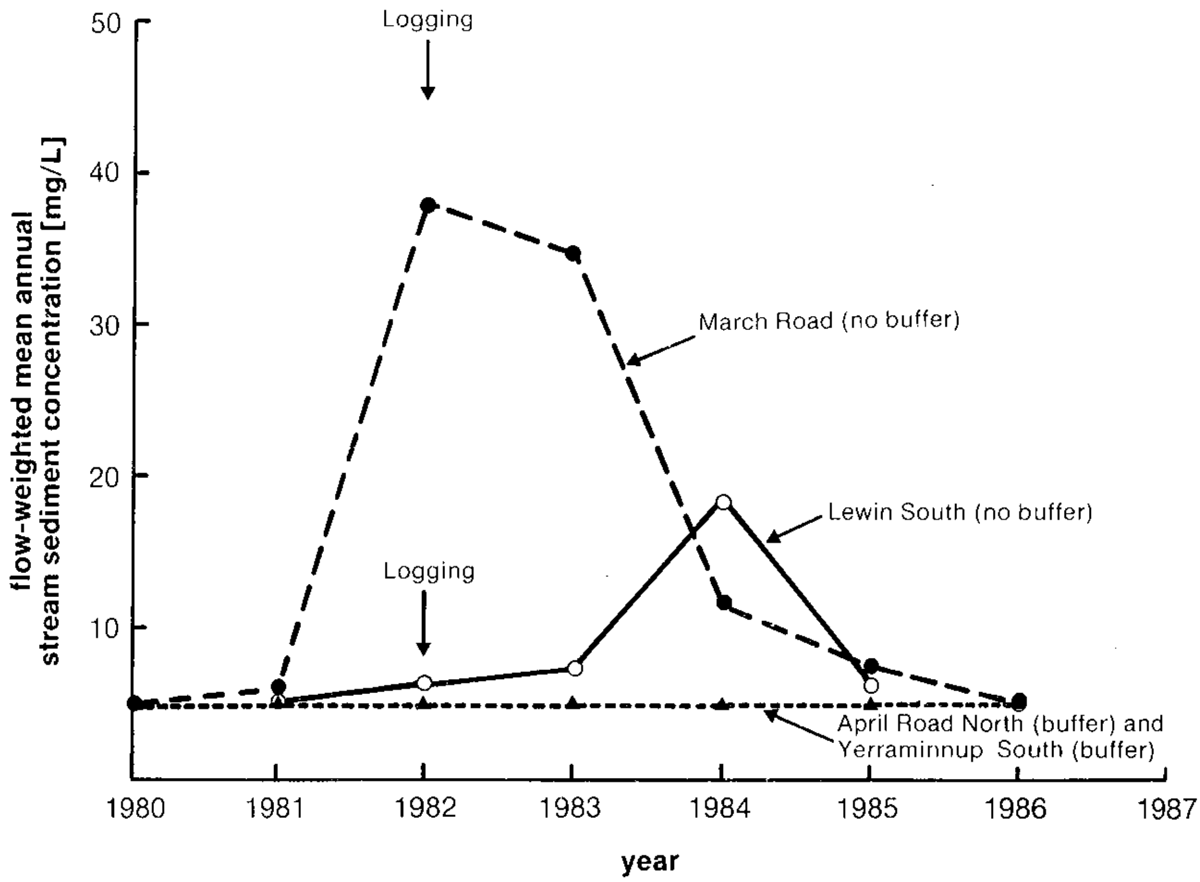

Figure 9
Changes in flow-weighted mean annual stream sediment concentration following logging

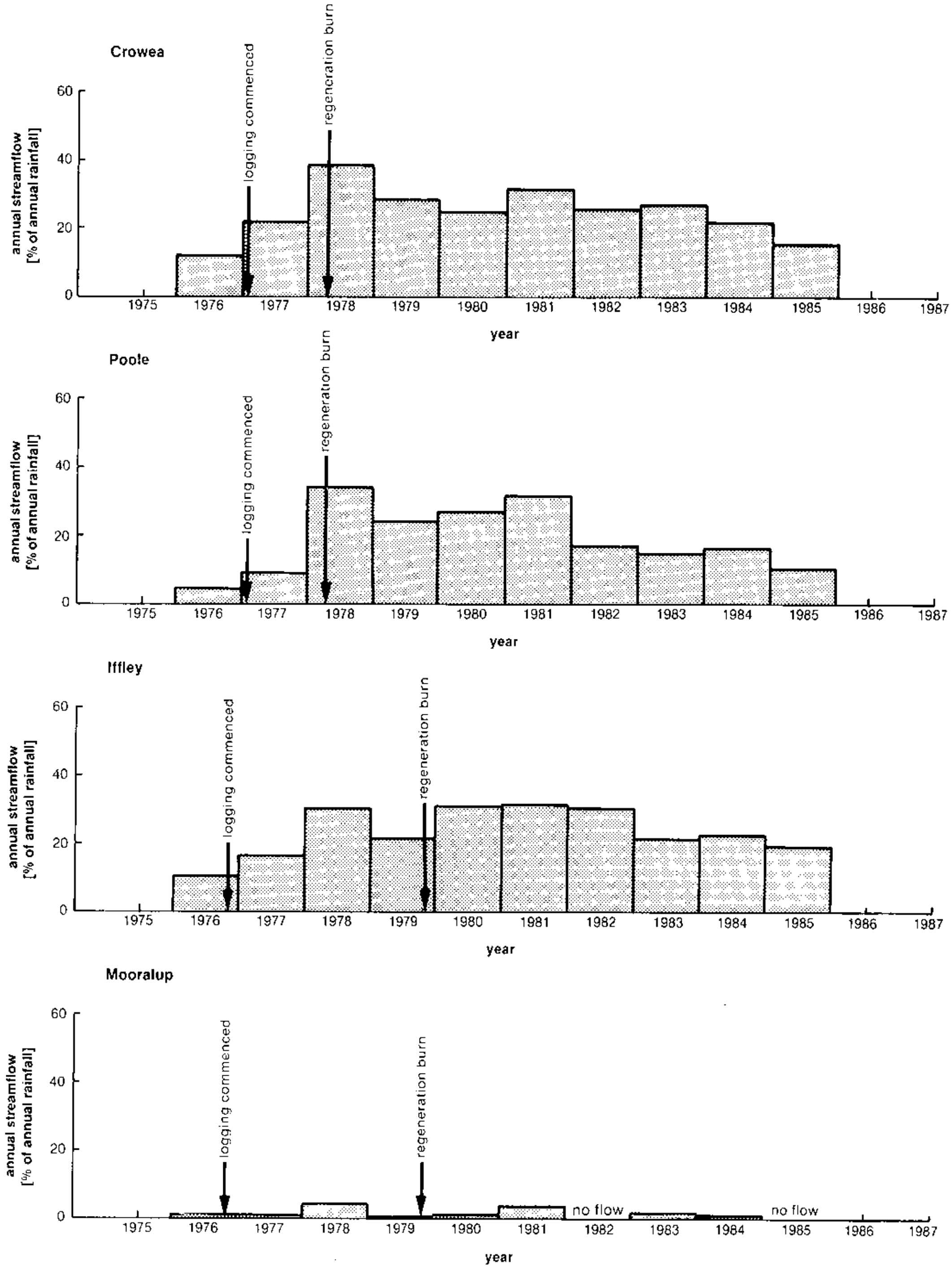

Figure 10
Annual streamflow in the four experimental coupes

5. *Discussion of Results*

Rainfall

The 10% lower than average mean annual rainfall over the study period probably influenced the magnitude of the hydrologic response to logging and subsequent regeneration, but not the general trends. The lower than average rainfall should be considered when interpreting the results and when reviewing forest management procedures.

Stream Salinity

In the context of the first objective of the research programme, clearfelling and a heavier selection cutting regime in the high and intermediate rainfall zones have led to temporary increases in annual stream salinity on treated catchments. However these increases have been small (150 mg/L TSS or less) and annual streamflows have remained within the fresh range (< 500 mg/L TSS).

A detailed review of leaf cover data for different aged stands following heavy logging and/or clearfelling (Stoneman *et al*, 1987) emphasised the temporary nature of the vegetation disturbance and confirmed earlier work on the rapid recovery of karri leaf area (Carbon *et al*, 1979; Grove and Malajczuk, 1985). Groundwater observations from the early warning project indicated that regrowth between two and four years old had already commenced depleting the additional groundwater accumulated since logging commenced.

The results from the paired-catchment project are preliminary. Accurate determination of the duration of the salinity elevation will have to await further years of post-treatment monitoring. Results from the coupe experiments suggest that stream salinity levels may return to pre-logging values in 10 to 15 years.

Most importantly, the largest salinity increases occurred in the intermediate rainfall zone where groundwaters were near to or currently discharging to the stream. No measurable increases in stream salinity occurred in the low rainfall zone, despite its higher salt storage, due to the greater depth to groundwater.

From a large-scale water resource perspective these temporary stream salinity increases are minor. Significant increases in the low-flow salinities were, however, observed in the intermediate rainfall zone under the most adverse conditions of current practice. Significant increases only occurred where groundwaters of moderate salinity were at or close to the stream bed prior to logging and where a stream buffer was not retained.

No problems were evident with vegetation regeneration in the groundwater discharging areas in March Road catchment where low-flow salinities of over 1500 mg/L occurred. Nevertheless, streams with salinities greater than 1500 mg/L are not suitable for human consumption. Such salinities can occur for periods up to several weeks at low flows at the commencement and cessation of flow each year. If these low-flow salinities persist for many weeks they could adversely affect drinking water supply systems based on small storages.

A return to wetter conditions in the region would tend to raise groundwater levels regionally above levels monitored through the study period. This would increase the potential for logging operations to mobilise soil solutes and increase low-flow salinities in the intermediate and low rainfall areas. However, the additional streamflow in wetter conditions would dilute much of the increased salt discharge. Means of modifying management practice to consider local risks of salt mobilisation are being developed and are discussed further in section 6.

Sediment Concentration

Considering the second objective of the research programme, measurable increases in sediment concentrations were observed for a period of 2 to 3 years after logging in the most adverse conditions of current operational practice. These disturbances are minor in the context of major developments of large water resources. They would, however, be of concern on an existing water supply catchment with small storages and short nominal retention time, as insufficient time would be available for turbidity levels to reduce in the storage. Summer logging combined with a stream reserve prevented any measurable increase in sediment concentrations.

Although the catchments where detailed sediment studies have been carried out were not the highest erosion hazard areas in the region, it is clear that significant benefits are available from the retention of stream buffers.

Long-Term Water Yield

The third objective of the research programme related to the long-term effect of logging and regeneration on catchment water yields. An important long-term consequence of the young re-growing forest is a likely reduction in water yield. This is not a major issue currently, but if all the stands were left unthinned, a significant reduction in water yields could develop at about the time the major water resources of the region are considered for development (30 years plus). On going monitoring to evaluate water yields in relation to forest density through time will be required. Thinning practices which optimise both timber and water yields may need to be developed.

6. *Management Implications*

The observed increases in salinity and sediment concentration resulting from intensive logging operations do not pose a threat to water resources. However every reasonable effort should be made to minimise these local and/or seasonal effects. The following guidelines indicate ways in which both water quality and timber availability can be simultaneously maintained or improved.

Low Rainfall Zone

For the past decade logging in the north-east sector of the Woodchip Licence Area has been restricted while the potential salinity hazard was under evaluation. Research has now shown that there is little risk if permanent groundwater levels are more than 5 metres below the soil surface in valley bottoms. Such areas could be made available for the combined sawlog/chiplog operations, although stream buffers of about 10% of the size of the upslope logged area should be retained. The risk of significant saline groundwater discharge under these conditions is low, even if above average rainfall occurred in the first few years following logging.

Some sites which may be slow to regenerate have been identified in this sector and modified logging and regeneration practices have been prescribed to achieve rapid regeneration. These practices aim to retain sufficient mature cover while also stimulating regeneration. They should be subject to ongoing evaluation and review.

While most of the north-east sector is likely to have groundwater at a greater depth than 5 metres, some areas may not and a series of wetter years could increase their extent. Practical techniques for identifying shallow permanent groundwater need to be developed and incorporated into routine planning of operations. Ideally, such techniques may be based on site-vegetation types and use simple vegetation indicators. Simple geophysical or shallow drilling methods may also prove necessary.

The layout and area of stream buffers should be matched to the risk of saline discharge from permanent groundwaters. Buffer areas should range upwards from the 10% (of the upslope logged area) for forest with permanent groundwaters at depths greater than 5 metres, to exclusion of intensive logging adjacent to shallow permanent groundwaters.

Intermediate Rainfall Zone

Minimising both stream salinity and sediment concentrations is desirable in this rainfall zone. As the chance of causing significant increases in low-flow salinities is highest in the intermediate rainfall zone, a larger retention of streamside vegetation than is currently practiced is required for a number of years to minimise groundwater discharge.

For sediment control, stream buffers would be desirable throughout the intermediate rainfall zone. For salinity control, buffers are required only where low-flow salinities of over 1500 mg/L TSS are likely to develop. The size of stream buffers should therefore reflect both the soil solute concentrations and proximity of water tables to the surface in stream zone areas. As in the low rainfall zone, practical field techniques for establishing these characteristics in the highly variable intermediate rainfall zone will be required. Practical definitions of the sizes and the subsequent management of buffer zones will need to be developed over the next few years. In the interim, the retention of stream buffers on all streamlines in the intermediate rainfall zone should be incorporated into new logging plans. The minimum width should be 10% of the upslope logged area or at least 50 metres on either side of the watercourse. Subsequent extraction of the timber resources from stream buffers where soil salinity is low can proceed once such areas can be readily identified. Phased logging (as discussed below) of areas upslope of minimum size stream buffers may be appropriate in some of the most salt prone areas of the intermediate rainfall zone.

High Rainfall Zone

From a salinity perspective there is no concern about intensive logging in the high rainfall zone. Increased sediment concentration is the only real concern in this rainfall zone. The introduction of permanent stream buffers on all streamlines is one means of minimising sediment concentrations but would result in a loss of valuable timber resources.

An alternative is to phase the logging operation. In any particular area, this would involve dividing the landscape into upslope and downslope segments of appropriate proportions. One of these segments would be logged first, followed by regeneration of the area for 3 to 4 years before the second segment is logged. Compared with the traditional method of logging both stream zones and upslope areas at the same time, the proposed phased logging should substantially reduce sediment movement to streams. Detailed prescriptions for such operations have been prepared and trials are underway. The impacts have been difficult to reliably quantify, although no major disturbance appears to have occurred. However, more accurate quantification of the effects of stream buffer logging is required.

Experience in this region and throughout the World has shown that inappropriately located or poorly designed or maintained haul roads can result in a significant increase in stream sediment concentration. Good design and maintenance can readily overcome this problem.

Existing and Potential Local Water Supply Catchments

Only about 1% of the region's water resources are currently utilized for public water supply and no substantial expansion is projected within the next twenty years. However, the impacts of logging on water quality must be considered where public supply systems are or will exist, especially if such systems were to be based on small volume storage. A conservative allocation of stream buffers is appropriate in such catchments. Minimum buffer widths should be at least 100m on all streams and logging should be restricted to summer only. Subsequent phased logging of stream buffers on existing catchments should only proceed where it can be expected that no temporary water quality loss will occur.

7. Future Research

The research programme has been in operation for about twelve years and has played a major part in improving the hydrologic knowledge of the region generally and in providing an initial quantification of the impact of the forest management practices associated with the Woodchip Industry.

The level of research effort has already been scaled down and emphasis placed on the most critical areas. Project 1 was completed in 1981 and all but groundwater monitoring on the early-warning project catchments (Project 4) was discontinued at the end of 1985. The major stream sediment sampling on all but one stream was discontinued at the end of 1986. However, the programme has not yet had time to fully quantify the hydrologic effects of forest operations. Only three years post-treatment data are currently available for the paired catchments. It is essential that this research continue to:

(1) determine the time required for groundwater levels in the early-warning research catchments to return to their pre-treatment levels;
(2) quantify the longer term water yield and stream solute concentration changes and groundwater responses on the more detailed paired catchments;
(3) evaluate the effectiveness of phased logging in minimising stream sediment and salinity concentrations, and groundwater responses, by logging the stream reserve on April Road North catchment;
(4) measure the long-term water yield response of regrowth karri forests at the Sutton Block catchments and determine appropriate thinning regimes.

Additional work will be required to provide more definitive advice on the design and management of stream buffers, particularly in the intermediate and low rainfall zones. If refinements to current management are to be implemented then the following additional research will be required:

(5) develop practical means of assessing the local risks of salt mobilisation and groundwater discharge in the intermediate and low rainfall areas;
(6) develop appropriate stream buffer definitions and subsequent logging prescriptions for stream zones based on the more accurate assessment of the local salinity and sediment risks.

8. *Conclusions*

Clearfelling in karri forest and heavy selection cutting in jarrah forest cause small, temporary increases in stream salinity and sediment concentration in local streams in the intermediate and high rainfall zones. These effects pose no threat on a regional water resources scale. However, brief seasonal peaks in salinity and/or sediment concentration on a local scale should be moderated by some refinement of management practices.

Annual stream salinity increases peaked at between 50 to 150 mg/L TSS although all annual stream salinities remained in the fresh range (below 500 mg/L TSS). The intermediate rainfall zone is the region where the highest temporary increases in salinity occurred. Under the most adverse conditions of current logging practice, salinities of over 1500 mg/L TSS, were recorded at low flows. Additional streamflow during the main winter months diluted these high salinities such that annual flow-weighted stream salinities remained in the fresh range. While these changes would be insignificant for moderate to large water resource developments, the seasonal peak effects would be undesirable in small storage volume public drinking water supplies. The temporary nature of increased salinities makes them far less serious than salinity deterioration resulting from agricultural development in the same region.

The risk of salt mobilisation and increased permanent groundwater discharge in the intermediate rainfall zone is very dependent on local hydrogeological characteristics. Refinements to current forest management practice should reflect these varying risks. Further work is therefore warranted to develop practical means of more accurately assessing local risks so that appropriate phased logging operations and stream buffer designs can be incorporated in the planning of logging operations.

In the low rainfall zone, despite high soil salinity concentrations, there is little salinity risk where permanent groundwater levels are normally more than 5 metres below the stream bed prior to logging. In these cases there is insufficient groundwater recharge, both in quantity and duration, to transport salts in the valley subsoils to the stream before the regenerating forest commences depleting groundwater. This finding contrasts with the dramatic effect of agricultural development in the low rainfall area. Therefore, subject to the provision of stream vegetation buffers, confirmation of the depth to saline permanent groundwater, and rapid regeneration, removal of both chipwood and sawlog timber should be permitted from the low rainfall zone.

The observed changes to the water and salt balances caused by the logging activities are likely to return to unlogged conditions within 10 to 15 years of the commencement of regeneration. Further monitoring of the paired catchments is required to confirm these results.

Stream sediment concentrations increased following logging but returned to pre-logging levels within four years of regeneration. Measurable increases in sediment can be avoided by restricting operations to summer only and by maintaining a stream buffer of nominal width of 100 metres on either side of the watercourse. Evidence to date suggests that the stream buffer vegetation is also important in delaying groundwater responses in valleys. Further monitoring will be required to determine this effect more clearly.

The increased understanding being gained through this research programme and forest management experience will ensure that appropriate improvements to forest management practice will be evolved and implemented to protect and improve the quantity and quality of the water resources of this region.

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Appendix

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Glossary

basal area	The cross-sectionional area of 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.
chiplog	A log of suitable grade for chipping but not suitable for sawn timber production.
chipwood	Wood in logs or mill residues suitable for chipping.
clearfelling	The felling of all trees, including unusable trees, carried out in a given area to achieve uniform, even-aged regeneration.
coupe	A discrete felling area.
cull treatment	Removal of inferior or defective trees.
cut-over area	An area that has been logged.
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.
flow-weighted mean	A mean calculated by dividing the quantity (e.g. salt load) by the total flow volume during the period in question.
groundwater flow	The flow of water in saturated aquifers.
head	The height of a column of static water that can be supported by the static pressure at the point.
infiltration	The passage of water through the surface of the soil, via pores or small openings, into the soil mass.
logging	Felling and hauling logs.
logging practice	The design, execution and regeneration procedures used when logging an area. Incorporates the planning of stream buffers and road alignments, the conditions imposed on the logging itself and the subsequent site rehabilitation methods employed.
natural regeneration	The renewal of a forest by self-sown seeds, advance growth or coppice.
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.
perched aquifer	An unconfined aquifer separated from the underlying permanent groundwater aquifer or bedrock by an unsaturated zone.
permeability	The ability of a soil or rock to transmit water.
recharge	Soil water which penetrates to a temporary or permanently saturated zone.
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.
sediment	Solid particles transported and/or deposited by fluvial means.
selection cutting	A silvicultural system in which trees are removed individually over the whole area to maintain the stand in an uneven-aged condition.
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 or growth.
stream buffer (syn. stream vegetation buffer)	An area of undisturbed vegetation adjacent to the stream.
stream reserve	An area of vegetation adjacent to the stream permanently reserved for conservation.
throughflow	Downslope flow of water occurring physically within the soil profile, under both saturated and unsaturated conditions.
turbidity	Sediment suspended in a fluid causing the diffusion of light; provides one measure of water quality.
variable source area	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 streamflow draining a catchment usually expressed as an annual average volume, or volume per unit area, or as a percentage of the annual average catchment rainfall.