Water Interactions with Land Use and Climate in South Western Australia

by N. J. Schofield

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Water Authority
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by

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PREFACE

This report is based on an oral and written presentation by the author to the Hydrology and Forest Practice Workshop, Canberra, November 13th-17th 1989, organised by the Forest Hydrology Working Group of the Australian Forestry Council. The emphasis of the report is on the interaction between forestry and hydrology but also encompasses a wider range of related land uses, particularly agriculture and bauxite mining. Some discussion is also given to climate change because of its topicality and relevance to south-west Western Australia. The material presented in this report covers some 15 years of research, principally by the Water Authority but in close collaboration with a number of other government agencies and industry.

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PART I : LAND USE/CLIMATE IMPACTS ON WATER RESOURCES IN FOREST CATCHMENTS

1. AGRICULTURAL CLEARING

1.1 Introduction

Western Australia was settled by Europeans in 1829. Growth in the population and agriculture was slow to 1900. However at the turn of the century agricultural development increased rapidly and vast areas of native forest and woodlands were cleared for the establishment of annual crops and pastures. The growth in agriculture is indicated by the area sown to wheat, the major cereal crop, in Fig. 1. Clearly identifiable are two periods of rapid expansion, 1900-1930 and 1955-85. The conversion of the native, perennial, deep-rooted vegetation to annual crops and pastures greatly altered the hydrological balance and brought about unforeseen problems of salinisation, erosion and eutrophication which have severely degraded rivers, soils, estuaries and wetlands. In the following the effects of agricultural clearing on stream yield and stream salinity are described along with governmental approaches to managing forest clearing.

1.2 Effects of Agricultural Clearing on Stream Yield

The effects of agricultural clearing on stream yield have been studied in some detail at Wights catchment (Ruprecht and Schofield, 1989) which was fully cleared in 1976. Wights has an area of 94 ha and an annual rainfall of ~1200 mm yr^{-1}. Streamflow was found to increase for seven years following clearing before levelling off at an increase of about 30% of rainfall (Fig. 2). The increase in streamflow was closely associated with rising groundwater levels and an increasing groundwater discharge area in the valley (Fig. 3), which led to significant increases in saturation excess overland flow and throughflow.

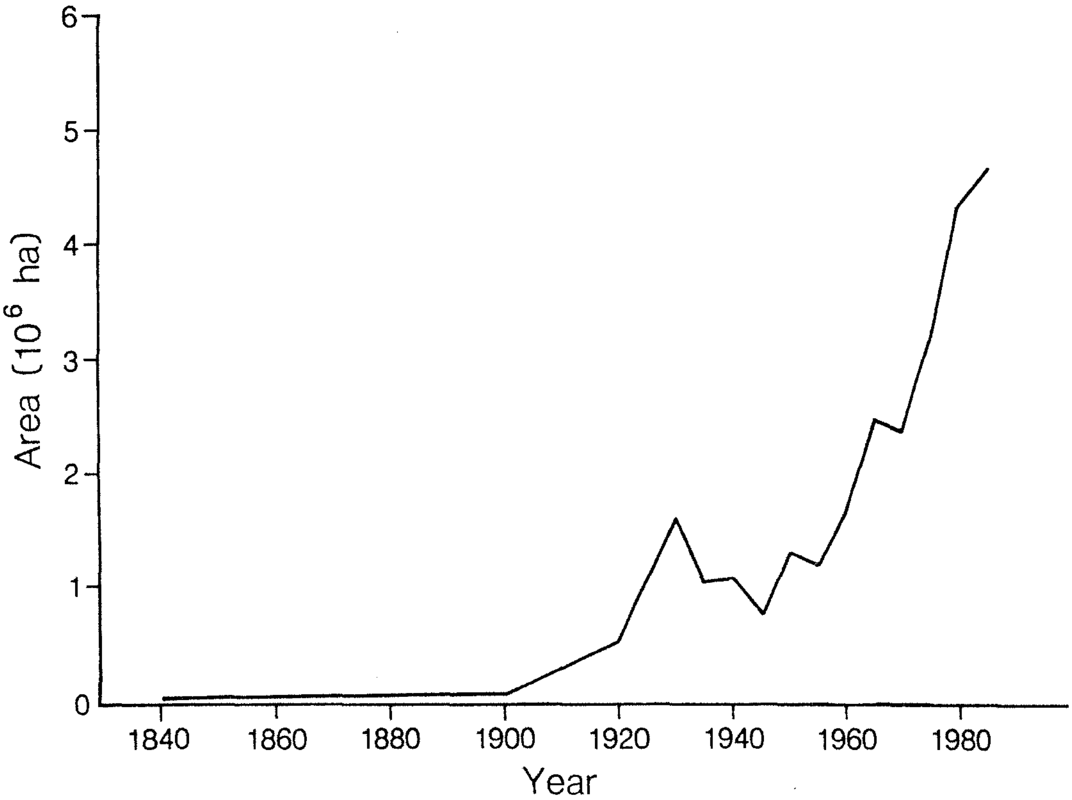


Figure 1 Area sown to wheat in Western Australia from 1840-1985 (source : Australian Bureau of Statistics, 1986)

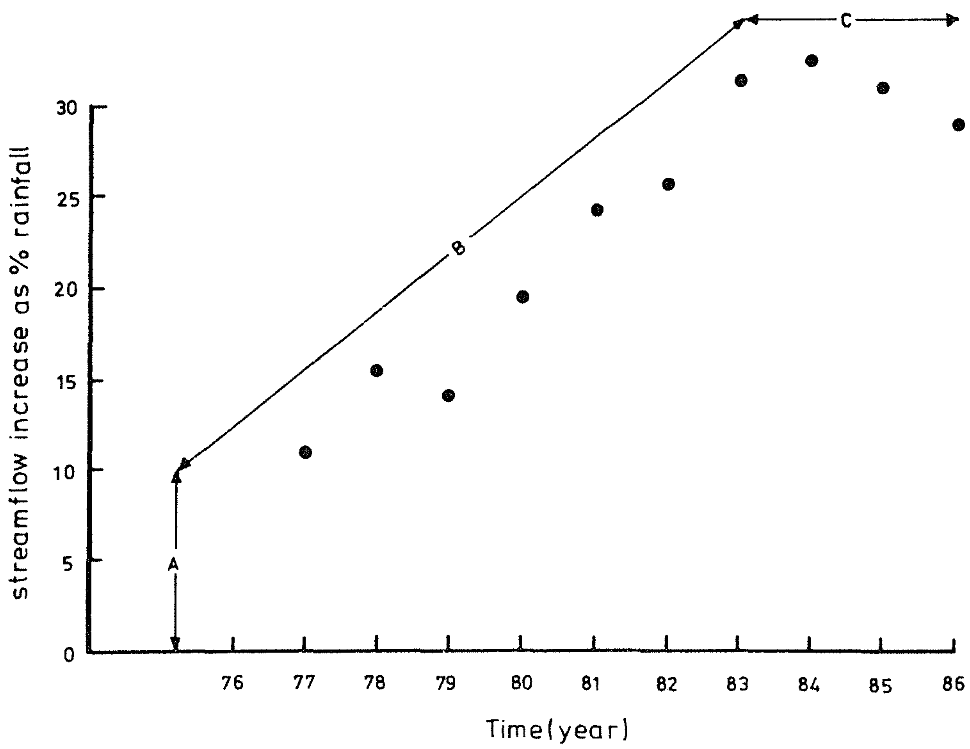


Figure 2 Time trend of streamflow increase for Wights catchment (after Ruprecht and Schofield, 1989)

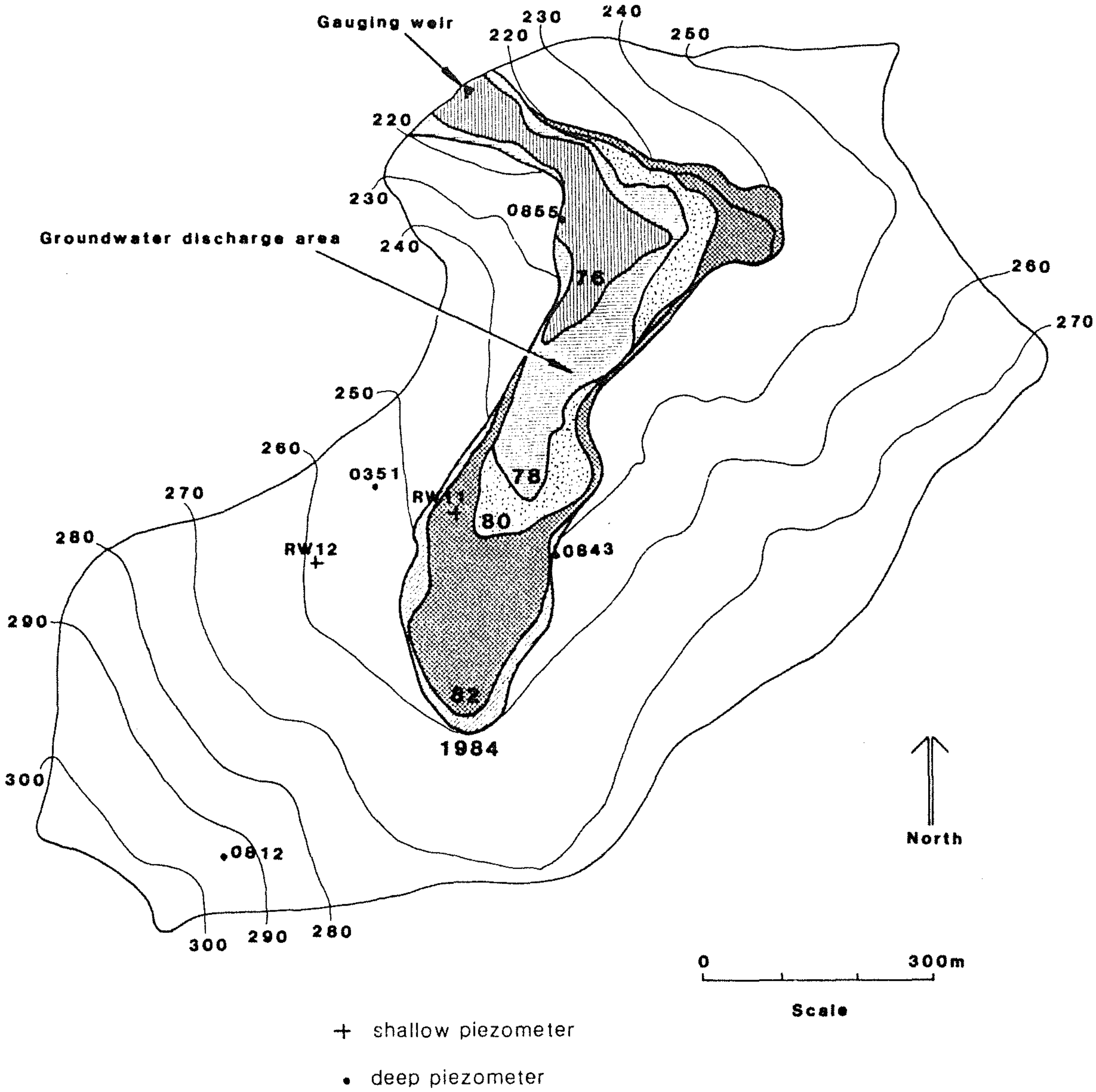


Figure 3 Growth of groundwater discharge area for Wights catchment (after Ruprecht and Schofield, 1989)

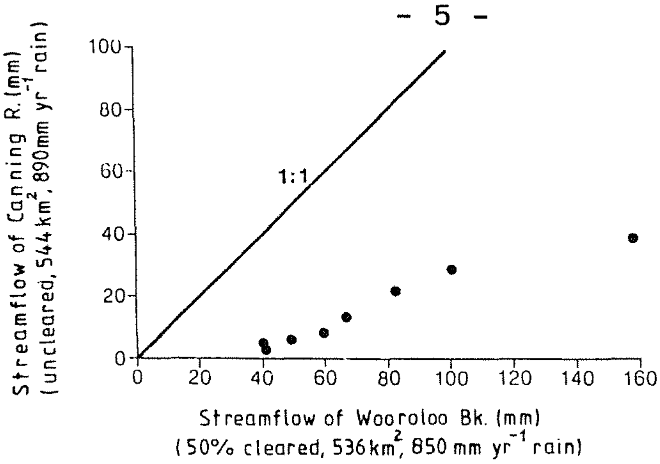
To determine whether the substantial streamflow increases observed for Wights catchment also occur at a larger scale and at lower rainfalls, suitable catchments with minor and major clearing were compared for stream yield (Fig. 4). These comparisons suggest that 3 to 4-fold streamflow increases occur on large catchments with lower rainfall in response to 50-60% clearing.

1.3 Effects of Agricultural Clearing on Stream Salinity

Stream salinisation is one of Western Australia's most serious environmental and resource problems. It is now widely accepted that stream salinisation in Western Australia has resulted directly from clearing native vegetation for the development of agriculture (Schofield et al., 1988). Traditional agricultural pastures and crops have lower annual water use than native vegetation (Greenwood et al., 1985). This results in a higher proportion of rainfall recharging groundwater. Groundwater levels consequently have risen following clearing (Peck and Williamson, 1987), bringing large quantities of previously 'stored' salt to the soil surface and streams (Williamson et al., 1987). This problem is particularly severe for the medium and lower rainfall areas (less than 900 mm yr^{-1}) of the south-west which are now predominantly under agricultural use (Schofield and Ruprecht, 1989).

Streams whose catchments lie wholly above 1100 mm yr^{-1} rainfall are essentially free of significant salinity risk despite the land use, although they may experience some increase in their salinity following forest clearing. Streams with catchments which extend inland to areas of below 1100 mm yr^{-1} rainfall are at high risk of salinisation, the risk increasing the further inland the catchment extends. The relationship between stream salinity, annual rainfall and agricultural clearing is shown for south-west catchments in Fig. 5.

Historically the high rainfall areas have remained largely under native forest because the soils were too poor for agricultural



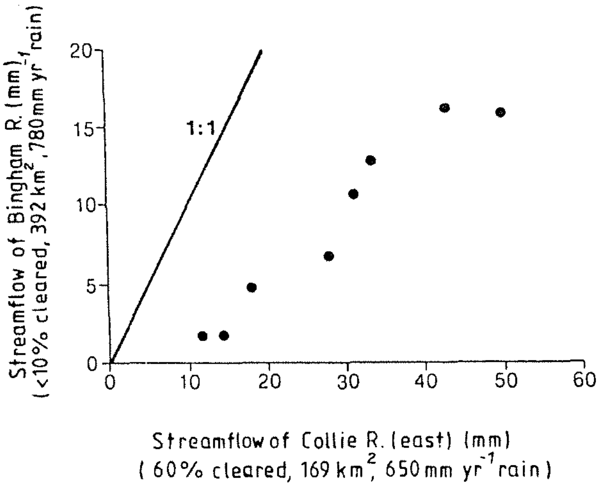


Figure 4 Annual streamflow comparisons of large catchments with minor and major clearing for period 1975-82

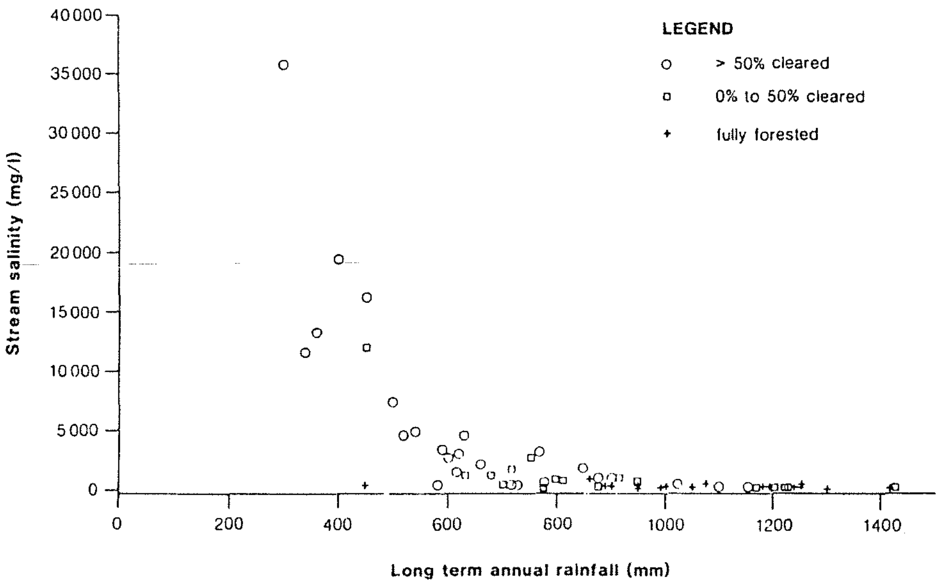


Figure 5 Relationship between average annual stream salinity and catchment average rainfall (after Schofield *et al.*, 1988)

use. These areas provide the bulk of the current surface water supplies to the south-west. Although these river catchments are not large in area, their water yields are relatively high due to high rainfall. Clearing and other activities in these areas are now closely controlled. Nearly 50% of the water resources of the south-west are fresh and protected by forest.

The major rivers and largest water resources of the south-west (i.e. the Avon, Murray and Blackwood) now have high salinities rendering them unsuitable for domestic water supply. The catchments of these rivers extend well into the low rainfall areas in which they are extensively cleared.

There is an intermediate group of rivers whose catchments have been less extensively cleared in their lower rainfall regions. These rivers typically have salinities in or close to drinkable levels but require active reclamation to maintain their water resource value. Included in this group are the Helena River (Mundaring Weir catchment), Collie River (Wellington Dam catchment), Denmark River and Warren River.

The salinity trends of all rivers with partially cleared catchments in lower rainfall areas have increasing salinity (Fig. 6). The rate of salinity increase is higher the lower the rainfall. Stream salinity increases have accelerated over the last 20 years. The stream salinity responses across a large catchment which exemplifies the two periods of rapid agricultural expansion are shown in Fig. 7. Stream salinities vary from fresh and stable in the higher rainfall area to brackish, rapidly increasing and highly variable in the lower rainfall area.

Stream salinities cannot continue increasing in the long term. In agricultural areas salt export from the landscape is considerably greater than salt input in rainfall. Thus salt stored in the soil is slowly being leached from the land. For the 600 to 900 mm rainfall areas, groundwater simulation studies suggest that stream salinities will continue to increase for another 20 to 50

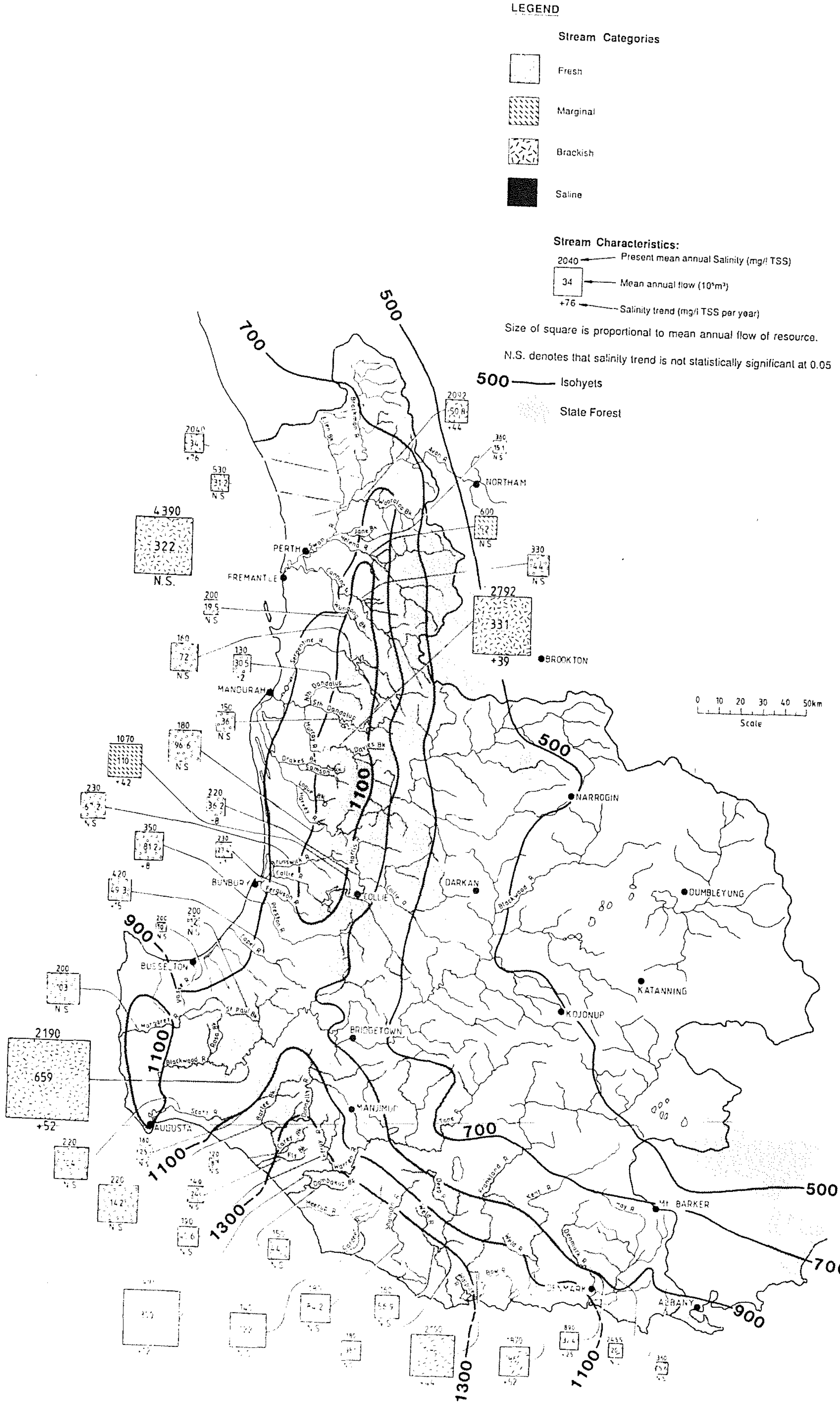


Figure 6 The distribution of surface water resources, salinities and rates of salinity change in relation to rainfall and forest cover (after Schofield, 1989)

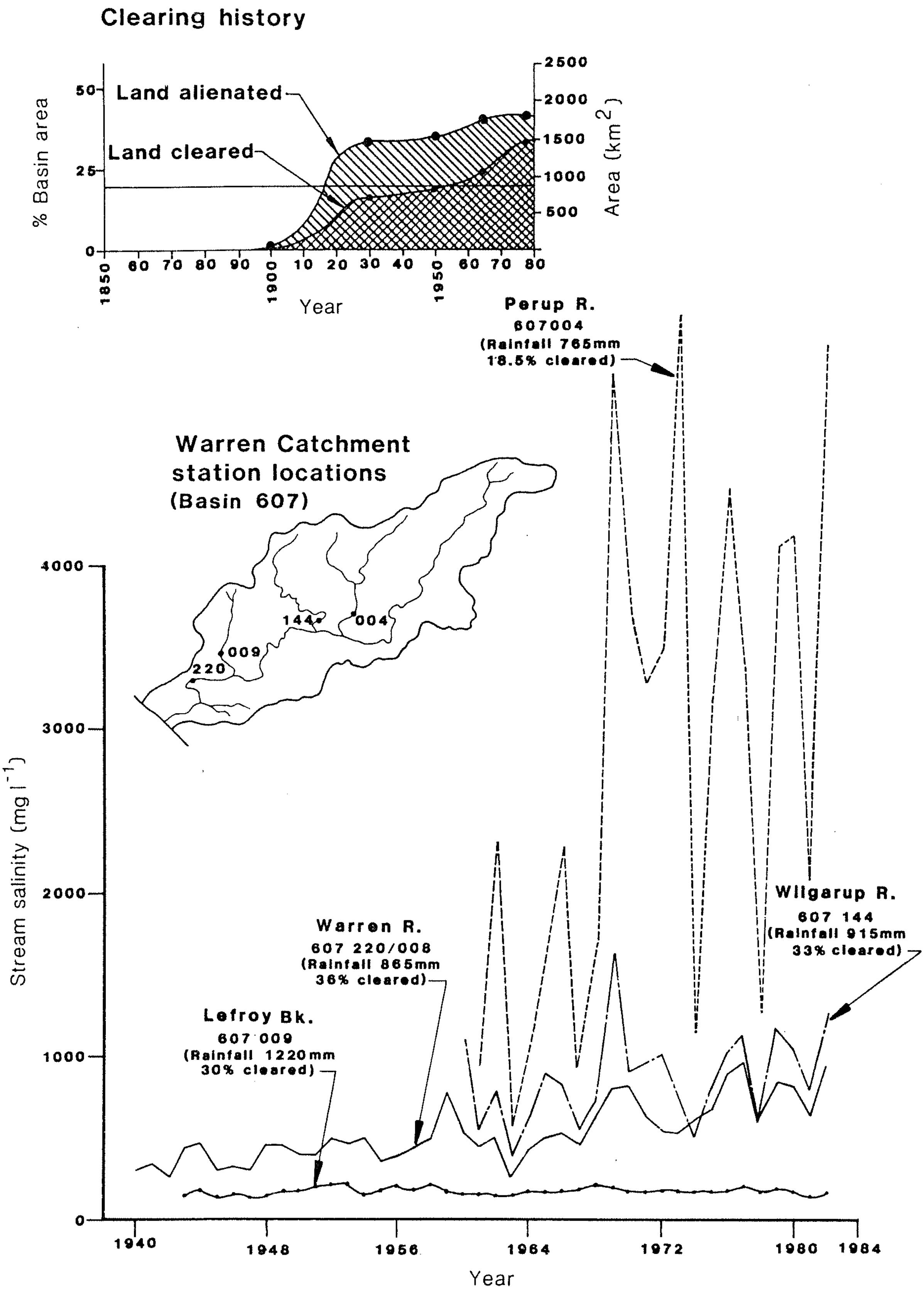


Figure 7 Stream salinity trends in response to clearing within the Warren catchment (after Schofield et al., 1988)

years before reductions caused by salt leaching commence (Hookey, 1987). However the time taken for stream salinities to reduce to a fresh level by this process could take from hundreds to thousands of years.

1.4 Management of Agricultural Clearing

The need to control both clearing and release of Crown land on water supply catchments was recognised in the early part of the century on Mundaring catchment. During the 1950s the need to control further alienation of Crown land on Wellington catchment was recognised when the dam was being raised to meet additional irrigation water demand and to provide the source for the Great Southern Towns Water Supply Scheme. Administrative action to control the release of Crown land on Wellington Dam catchment and the Kent and Denmark River catchments proceeded in 1961. In 1978 a State Cabinet decision was made to halt all alienation of Crown land between the Collie River and the Kent River to protect other potential water reserves in the lower south-west.

Through the 1960s there was a growing awareness that control of alienation of Crown land would not be sufficient to maintain satisfactory salinity levels in a number of major water resources. Action would be required to halt clearing on land already alienated. In 1976 amendments to the Country Areas Water Supply Act (1947) were passed by both Houses of Parliament. The legislation made it an offense to clear or destroy native vegetation without a licence. The legislation was applied initially to the catchment of the Wellington Dam. In 1978 the legislation was extended to four other critically important water resource catchments. These were Mundaring reservoir catchment and the Denmark, Warren and Kent River catchments. The catchments were carefully selected to represent those most sensitive to further agricultural expansion.

Catchments which had brackish or saline streams which could not be easily returned to potable levels were not included under the legislation. Also not included were catchments that drained predominantly State Forest and were fresh and unlikely to become saline if the small amounts of private land in their catchments were cleared.

Under the clearing control legislation small scale essential clearing is licenced but large-scale agricultural development is not permitted. Affected farmers can claim compensation for their inability to further develop their farm enterprise.

The clearing controls have restricted agricultural development from approximately 1200 square kilometres in the more reliable rainfall areas of the south-west. Nevertheless this represents only 0.7% of the 180 000 square kilometres of farmland within private holdings in the agricultural areas of south Western Australia. Loss of this agricultural production potential has been accepted as a necessary consequence of protecting the five most important marginal water resources. The total expenditure on compensation associated with clearing controls has been $35 million over 11 years (Water Authority of Western Australia, 1988).

Administration of the clearing control legislation has not been without its difficulties. Initial problems in the definition of clearing arose where regrowth had occurred following earlier clearing. Also some areas of forest, usually the smaller clumps of trees in grazing areas, for which compensation had been paid, have not been fenced to exclude stock. The long term protection and regeneration of these areas is of serious concern. Although it is the responsibility of the landowner to ensure the maintenance of the indigenous bush, identifying any gradual decline in forest cover will be difficult and implementing remedial action will be a major limitation to the protection of remaining bush on farmland due to the high cost of fencing.

2. BAUXITE MINING

2.1 Introduction

Bauxite mining began in the jarrah (Eucalyptus marginata) forest of south-west Western Australia in 1963 when Alcoa of Australia Ltd. opened its first mine at Jarrahdale. Since then additional Alcoa mines opened at Del Park (1972), Huntly (1976) and Willowdale (1984) (Fig. 8). All these mines are in the western high rainfall (>1100 mm yr^{-1}) zone of the jarrah forest (Fig. 8). The Del Park mine will close in 1990. In 1988, 19.5 million tonnes of bauxite were extracted from these mines. Over the year 10/88 to 9/89, 488 ha of jarrah forest were cleared by Alcoa for mining. Since bauxite mining began, Alcoa has cleared 6129 ha of jarrah forest, of which 4406 ha have been rehabilitated to date. Alcoa's mineral lease covers 1.2 million hectares of the Darling Range of which 700,000 ha are State Forest (Fig. 8). However over 90% of estimated bauxite reserves within Alcoa's lease occur in the 400 000 ha Principal Mineralized Area denoted in Fig. 8. Approximately two thirds of Alcoa's bauxite reserves lie in the high rainfall area (>1100 mm yr^{-1}). The mined ore is transported to Kwinana (by rail), Pinjarra (by conveyor) and Wagerup (by conveyor) where it is refined to alumina.

In 1983 Worsley Alumina Pty. Ltd. opened a bauxite mine at Mount Saddleback towards the eastern, low rainfall edge of the jarrah forest (Fig. 8). This mine is unlikely to affect the local water resources and is not considered further here.

The major impacts of bauxite mining activities to date have been on stream yield and stream turbidity. Erosion and sediment generally have not been problems due to adequate minesite rehabilitation measures. In the future (~30-40 years), as mining moves eastwards into higher salt storage areas (<1100 mm yr^{-1} rainfall), the potential impact on stream salinity will be a major issue. Alcoa has made a commitment that 'mining will not take place in the eastern, lower rainfall portion of Alcoa's lease until research shows that mining operations can be conducted without significantly increasing the salinity of water

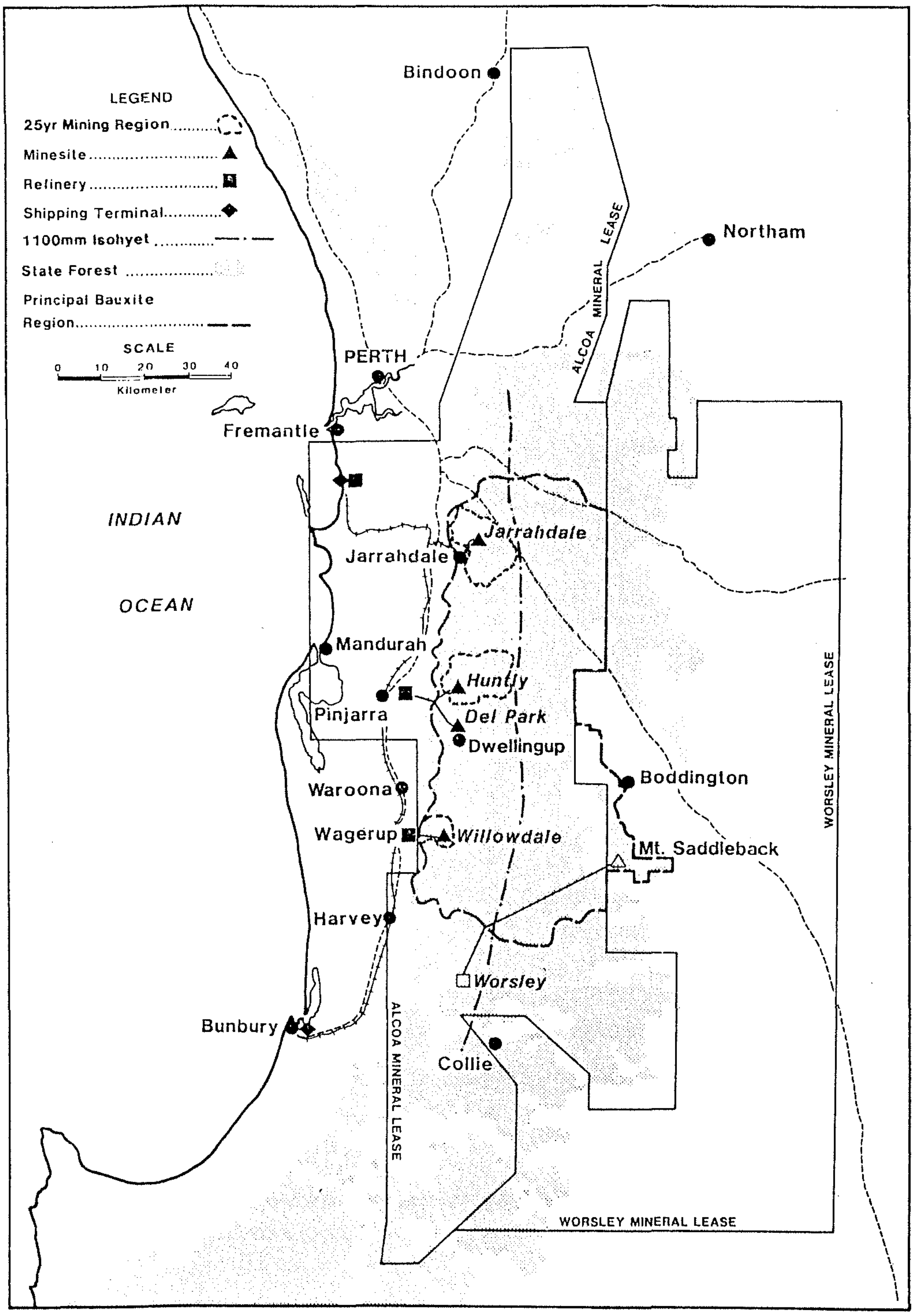


Figure 8 Mineral leases and minesites in south-west Western Australia (source : Alcoa of Australia Pty. Ltd., 1990)

resources'. Research to address this problem commenced in the early 1980s.

2.2 The Mining Sequence

The first step in the mining process is the logging of commercial timber from the proposed mining area. Remaining forest is then bulldozed, stacked and burnt. The topsoil overlying the caprock is removed wherever possible in two stages: the first 5 cm is stripped and transferred directly to a mined area undergoing rehabilitation; the remaining topsoil (typically about 35 cm depth) is then removed and stockpiled adjacent to the pit being mined. Removal of the topsoil leaves the caprock exposed, which is blasted. The blasted caprock and the underlying 'friable bauxite horizon' is excavated down to the depth where the reactive silica levels become too high or the alumina grade becomes too low for economic refining of the ore. This can occur at or somewhat above the pallid zone depending on local variations in geology. Nevertheless the mining usually involves the removal of 3 to 5 metres of the soil profile, although a depth of 15 metres was mined at one site.

2.3 Rehabilitation

2.3.1 Rehabilitation objectives

Development proposals for the Wagerup and Worsley projects post-dated the Enviromental Protection Act of 1972 and therefore required the submission by the companies of Environmental Review and Management Programmes (ERMPs). In both cases the programmes which were approved legally commit the companies to comprehensive rehabilitation, environmental monitoring and research (Alcoa 1978, Worsley 1979). The rehabilitation objective embodied in each programme is to regenerate land that is able to meet the land use requirements of the State.

Planning of land use requirements by the State was upgraded in the 1970s and 1980s in anticipation of conflict between rapidly expanding, competing uses. This culminated in a series of regional management plans (Department of Conservation & Land Management 1987a, b, c) which were subject to public review. With respect to mining, the objective of rehabilitation is to regenerate stable ecosystems and integrated landscapes designed to restore or enhance the following land values:

- Water values: To ensure that mined areas provide acceptable water quality and quantity.

- Timber: To grow a forest which has the potential for eventual sawlog production.

- Recreation: To maintain existing recreation values where possible and to provide increased opportunities for forest-based recreational activities.

- Protection: To conserve the residual soils, to control dieback (Phytophthora cinnamomi) spread, and to ensure that unacceptable fire hazards do not accumulate.

- Landscape: To create a rehabilitated landscape visually compatible with the adjoining remnants of indigenous forest.

- Conservation: To re-create, in the long term, floral, faunal and soil characteristics compatible with the remnant indigenous forest.

2.3.2 Management of rehabilitation operations

During 1980 the Forests Department coordinated the preparation of the first comprehensive statement of objectives, techniques and 'success' criteria for rehabilitation operations. This prescription became known as 'Rehab. 80' (Underwood, 1980). Annual reviews are carried out to incorporate new information. The current prescription, 'Rehab 89', is presented in Appendix I. This prescription represents a major advance as a statement of strategies for rehabilitation, and in the control of field operations. They are also an effective avenue for introducing new research results into operations. A comprehensive description of the rehabilitation process is given in Nichols et al. (1985) and Bartle and Slessar (1989).

2.3.3 Development of minepit water control practices

Rehabilitation commences with landscaping of pit walls and floor, followed by deep ripping to relieve the compaction of the minepit floor, thus favouring infiltration of water. The operation involves ripping with a 'winged' tyne to maximise uplift and soil fracture and can be done on the contour to promote infiltration by providing surface depression storage. Then banks, channels and sumps are established to create a stable water-holding or water-conducting system. The system is designed to cater for the surface water runoff that would arise from a 1 to 10 day storm event with a recurrence interval of 15 years.

Up to 1981 the objective of minepit drainage was to detain all runoff within the minepit until it could be absorbed by infiltration. This method, though highly developed, has several deficiencies:

- it requires large water-holding structures, creating an undesirable terrain;

- it favours dieback by ponding water within the minepit and by contributing to seepage downslope from the minepit;

- it is not likely to be appropriate for use in the saline zone, due to the scope for salt mobilization.

It was therefore decided to pursue the development of a system designed to collect runoff with low profile banks, and to conduct it downslope on stabilized waterways to temporary sumps before discharge overland into streams. However winged tyne ripping has reduced the amount of runoff from minepits to the extent that contour banks are now rarely used. The size of water retention structures has also been greatly reduced.

The practical development of ripping and drainage has been paralleled by an increasing understanding and quantification of minepit hydrology. A model has been developed (The Rehabilitation Earthworks Design Model, Croton and Tierney, 1983) and is used operationally to specify drainage design for either water infiltration or collection systems for any minepit.

2.3.4 Minepit revegetation

Understorey re-establishment has been enhanced by spreading native seed and utilizing the natural seed load in topsoil. Research has shown that 'double-stripping', where the top 5 cm is removed and immediately re-spread, while the remaining 35 cm is stockpiled, leads to the return of a wider diversity of understorey species (Nichols and Michaelson, 1986). Trials with high rates of understorey seed and fertilizer application have produced a rapid and dense vegetation cover, attaining Leaf Area Indexes greater than 4 in 4 years (RSC, 1990). This rapid growth has benefits for water and erosion control.

Jarrah comprises from 0% to 80% of the overstorey seed/seedling mix depending on the dieback status and drainage characteristics of the site. If the dieback hazard is low (usually freely-draining upland sites) then native trees with predominantly jarrah are returned. If the dieback hazard is moderate to high, then dieback resistant species are introduced. In low moist areas, *E. patens* and *E. calophylla* are used while in areas prone to waterlogging *E. patens*, *E. megacarpa* and *E. rudis* have been established. In freely draining areas where dieback is still a risk, *E. wandoo*, *E. resinifera* and *E. maculata* have been widely planted in the past. However, plantings in recent years have made exclusive use of jarrah forest species.

Tree establishment has generally been by hand planting of 6-month-old nursery seedlings at a density of 625 seedlings per hectare (4 m x 4 m spacing). This has recently been increased to 1250 ha^{-1}. Trials in the past have indicated that trees also readily establish from broadcast seed (Bartle *et al.*, 1978). This direct seeding is now being carried out on the majority of sites.

2.4 Effects of Bauxite Mining on Stream Yield

The effect of bauxite mining and rehabilitation on stream yield in the high rainfall zone has been evaluated by comparing two mined catchments, Seldom Seen (7.5 km^2) and More Seldom Seen (3.3 km^2) with an undisturbed forest control catchment, Waterfall Gully (8.7 km^2) (Fig. 9). Mining on the catchments began in 1967/68. By 1981, 38% of More Seldom Seen and 27% of Seldom Seen had been mined and 21% and 17% respectively rehabilitated. At this time the reforestation stands had reached an average age of 5-6 years.

Cumulative areas cleared/mined and rehabilitated are compared to stream yield changes over time for Seldom Seen and More Seldom Seen in Fig. 10. The average increase in yield since mining commenced is 50-75 mm (20 to 30% of pre-mining flows). The stream yield increases tended to increase with time and were significantly correlated with the total area cleared/mined. There was also evidence that increases tended to be larger in wetter years. In the longer term, however, stream yields are expected to decline as the area and density of reforestation stands increase.

2.5 Effects of Bauxite Mining on Groundwater Levels

The impact of bauxite mining and rehabilitation on groundwater levels is important for potential salinity effects in lower rainfall areas, since significant increases in stream salinity are brought about by increased groundwater discharge. Groundwater level responses have been monitored at Del Park where mining took place in 1976 and rehabilitation was completed by 1978. In general the net yearly changes in groundwater piezometric levels have been difficult to attribute unambiguously to bauxite mining. Most of the observed changes have been within the range of responses of forested sites. However, increasing piezometric levels downslope of pits were identified at two locations and these are at least 0.2 m yr^{-1}. Peck (1983) analysed the change in minimum piezometric elevations from 1975 to 1981 for two groups of bores on Del Park catchment -

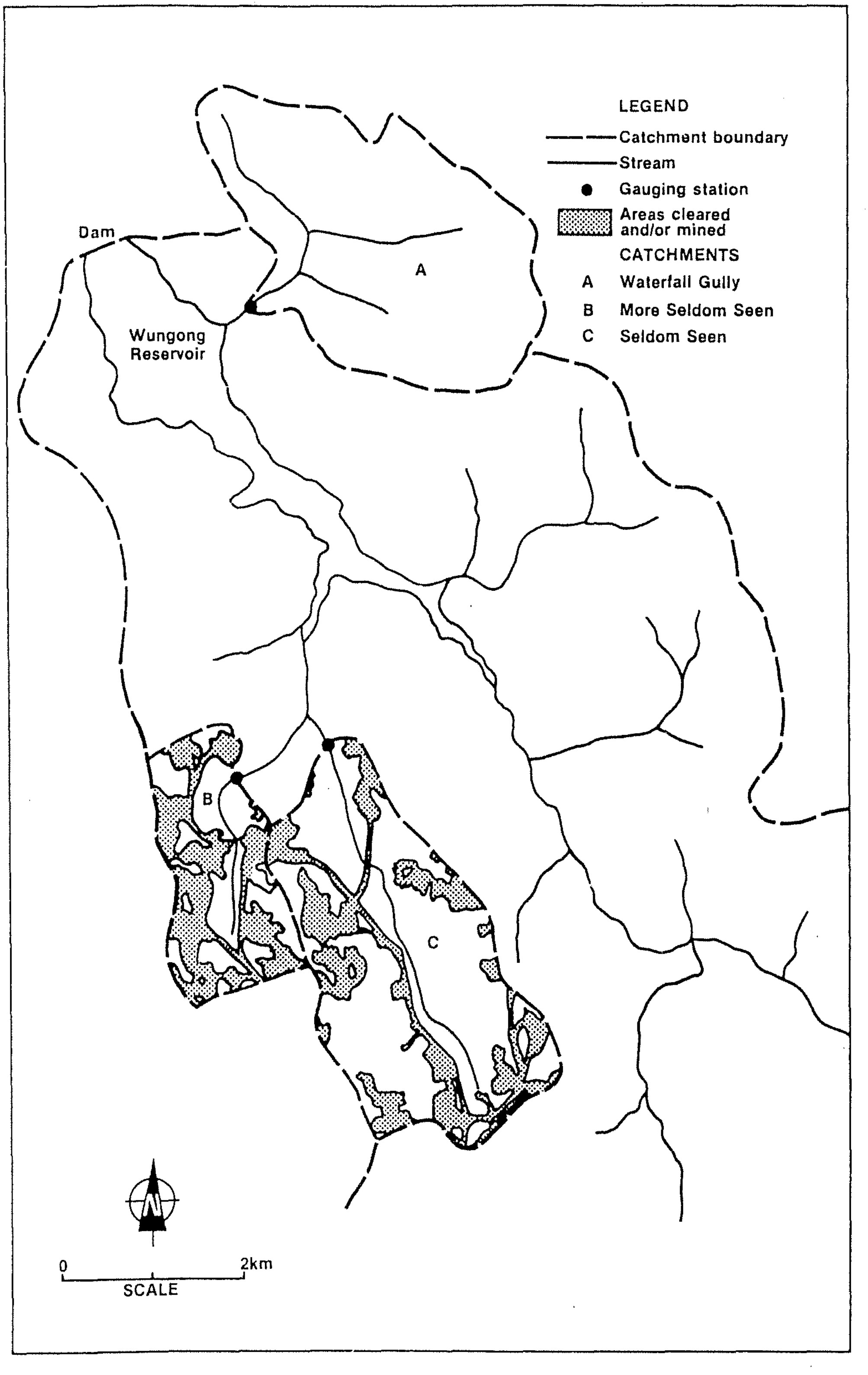


Figure 9 Locations of Waterfall Gully, Seldom Seen and More Seldom Seen catchments showing areas cleared and/or mined

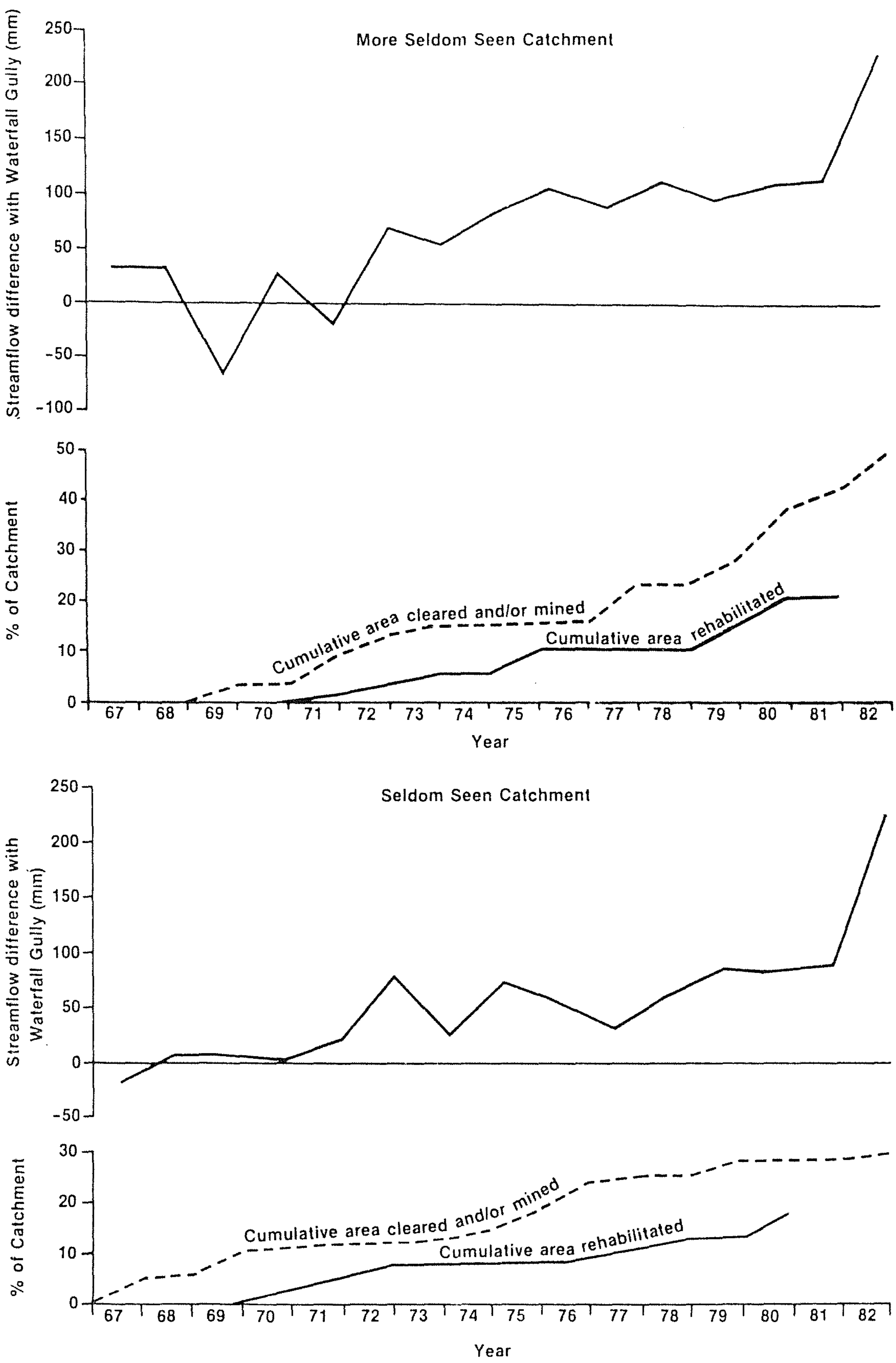


Figure 10 Changes in annual streamflow relative to Waterfall Gully and their relation to clearing, mining and rehabilitation in Seldom Seen and More Seldom Seen catchments (after Steering Committee, 1984)

one group affected by mining (14 bores) and the other in forest (20 bores). Over the six year period a net relative increase of 2.0 metres was calculated between the mean of the bores affected by mining and the mean of the bores which remained under forest.

2.6 Turbidity Control Measures

The major water quality problem in current mining areas is turbidity. The turbidity is due to the release of clay particles into suspension following soil disturbance. Haul road drainage is the major source of turbid minesite runoff. Turbid runoff is treated on site with sediment basins, vegetative filters and other sediment handling techniques. Treatment of this runoff by combinations of these techniques has proved successful in preventing the intrusion of turbid plumes into catchment reservoirs. Investigation of flocculant dosing systems has identified flocculant pellets as a potential turbidity control method in more sensitive areas.

Turbid surface runoff is contained within minepits and occurs primarily during the mining operation (clearing to rehabilitation) and in the first year of rehabilitation. Any potential turbid discharges from minepits must pass through sediment treatment structures similar to those used for haul road drainage. On completion of mining contour ripping and fast generation of understorey and ground cover rapidly reduces surface runoff and the levels of sediment that it carries.

Long term and short term turbidity monitoring programmes have been set up around minesites. Turbidities exceeding 25 NTU require immediate investigation and identification of the source. Turibidity data from stream monitoring sites downstream of the Jarrahdale, Del Park, Huntly and Willowdale minesites, compared to control forested water supply catchments are given in Table 1. Significant increases in turbidity in the mining catchments relative to forest are apparent but there are relatively few instances of turbidity exceeding 25 NTU.

Table 1. Turbidity of Mined and Forested Catchments
(Data from Alcoa of Australia to 31 December 1989)

Minesite	Predominant Land Use	Station ID	Pre 1983				1983 to 1989				All Data				1989 Data	
			No. of Samples	Mean	Max	No. >25	No. of Samples	Mean	Max	No. >25	No. of Samples	Mean	Max	No. >25	Mean	No. >25
Jarrahdale	Forestry/ Water Supply	TN14	1157	1.5	28.0	2	3130	1.3	37.0	3	4287	1.3	37.0	5	1.4	0
Jarrahdale	Mining/ Forestry	WG02	2639	1.1	32.0	1	5587	1.3	85.0	4	8226	1.3	85.0	5	1.2	0
Del Park	Mining/ Forestry	MP21	721	3.4	95.0	9	1667	6.5	200.0	78	2388	5.6	200.0	87	Closed	
Huntly	Mining/ Forestry	LO16	Not Sampled				762	3.9	64.0	18	762	3.9	64.0	18	1.7	0
Willowdale	Forestry/ Water Supply	SM17	811	1.1	7.7	0	3987	1.0	27.0	1	4798	1.0	27.0	1	0.8	0
Willowdale	Construction/ Mining/Forestry	SM34	1410	3.9	73.0	30	3927	3.3	200.0	46	5337	3.5	200.0	76	2.4	0
Willowdale	Mining/ Forestry	SM39	Not Sampled				258	1.0	12.0	0	258	1.0	12.0	0	0.9	0
Willowdale	Forestry/ Water Supply/ Pre-mining	SM41	Not Sampled				918	1.1	10.7	0	918	1.1	10.7	0	1.1	0

NOTES : 1) Pre-mining logging operations commenced in SM17 catchment in 1989
2) SM41 is downstream from SM17
3) MP21 closed April 1988
4) Turbidity units are NTU

3. IMPACT OF LOGGING ON THE WATER RESOURCES OF THE SOUTHERN FORESTS

3.1 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 (E. diversicolor) and jarrah (E. marginata) forests. The development of a woodchip industry to utilise non-sawlog grade marri (E. calophylla) 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 to co-ordinate the research programme. 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.

3.2 Description and History of the Woodchip Licence Area

The Woodchip Licence Area is centred on the town of Manjimup (Fig. 11) and covers 884 100 ha 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. The mean annual pan evaporation varies from 1150 mm in the south-west to 1450 mm in the north-east. In winter, rainfall exceeds pan evaporation and in summer, pan evaporation exceeds rainfall.

Within the area are 176 600 ha of karri forest, and 418 800 ha 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, 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 in the southern forests began before the turn of the century. Planned forest management began some years later with

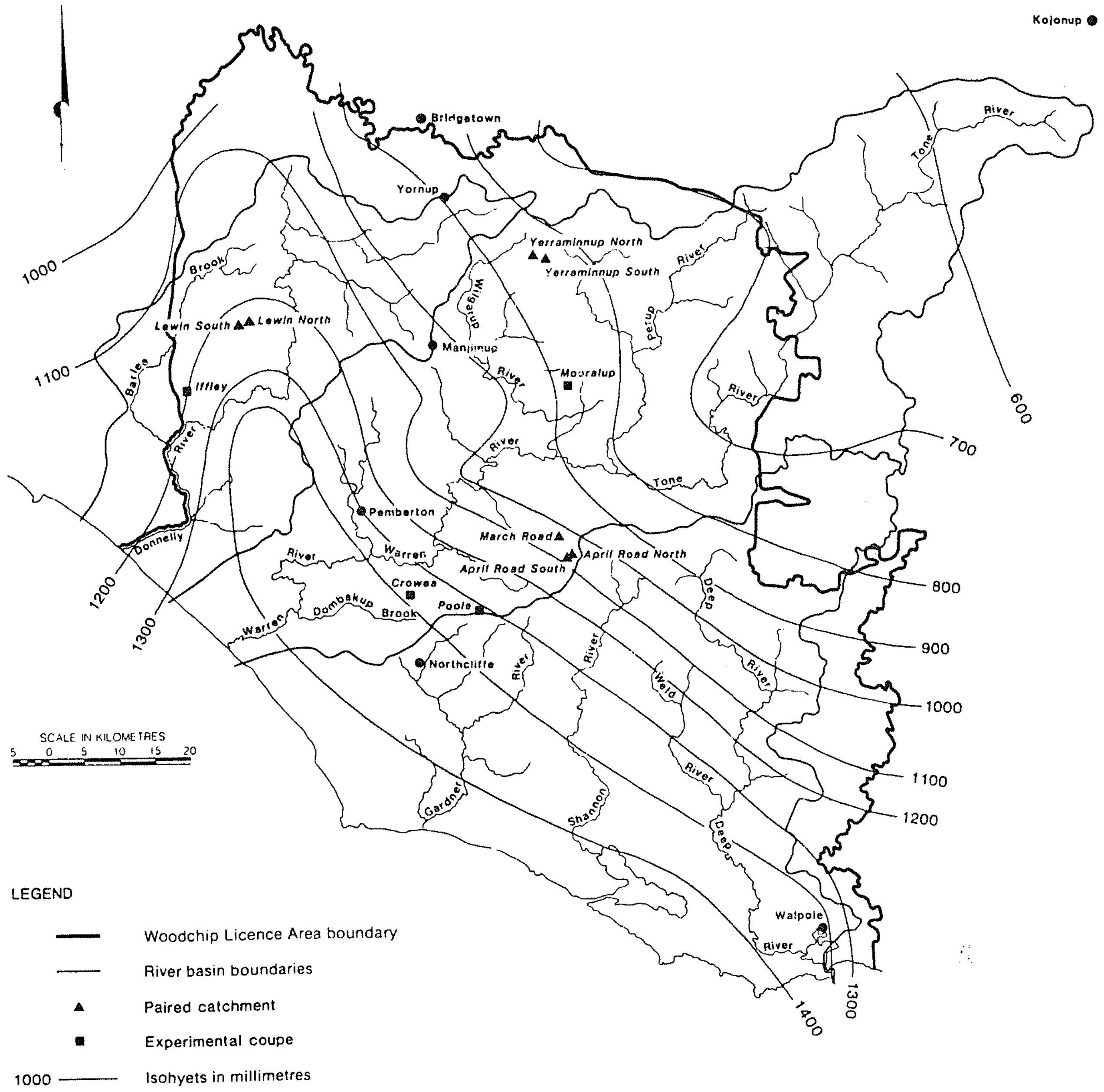


Figure 11 Location of paired catchments and experimental coupes in the Woodchip Licence Area (after Steering Committee, 1987a)

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 of 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. Cut over areas from 1975 to 1985 are shown in Fig. 12. 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 silvilcultural practices are described by Bradshaw (1985, 1986).

3.3 Research Programme

The main objectives of the research programme were:

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

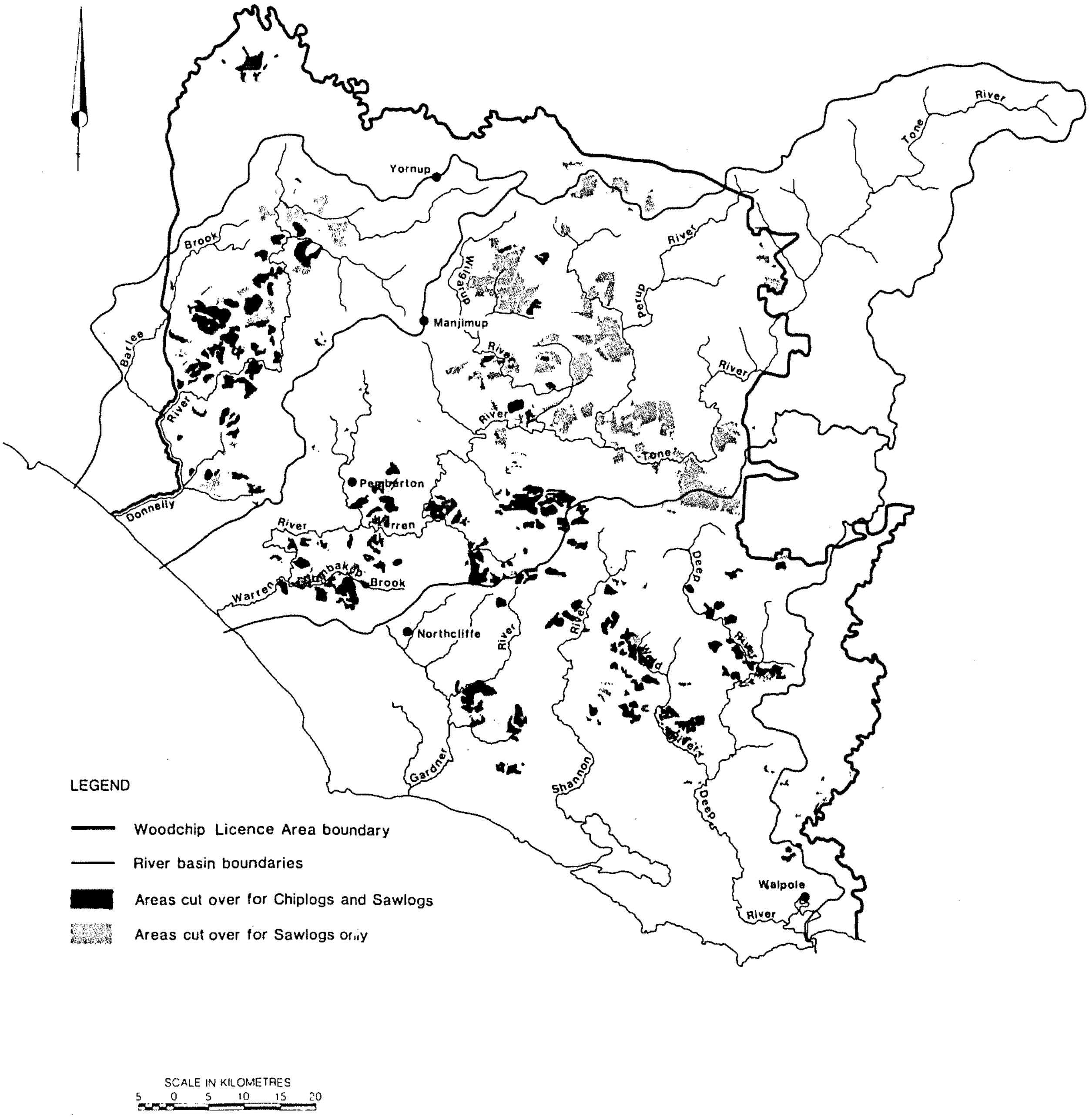


Figure 12 Forest cut-over in the Woodchip Licence Area from 1975-86 (after Steering Committee, 1987a)

(ii) to consider the long term effects (20 to 100 years) of logging and regeneration on water yield; and

(iii) 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 (Fig. 11). The characteristics and treatments of these catchments are summarised in Table 2. Rainfall, the quality and quantity of stream discharge and groundwater responses were monitored on all catchments. Four catchments (termed experimental coupes in Fig. 11) 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 has eight years of post-treatment data analysed.

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 have been analysed.

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

Table 2
Characteristics of Experimental Catchments

(a)

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	jarrah-marri and	1240	1102	133
Lewin South	red earths	karri	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	jarrah-marri	850	760	253
Yerraminnup South	yellow podzolics		830	746	183

Treatments applied to experimental catchments

(b)

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

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.

3.4 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.

The vegetation regenerated quickly in all rainfall zones (Fig. 13). In karri stands vegetation cover approached pre-logging levels within 5 to 10 years and while 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.

3.4.1 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 (Fig. 14). 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 (Fig. 15).

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 yr^{-1} (low rainfall region) than in areas with greater than 900 mm yr^{-1} (intermediate and high rainfall regions).

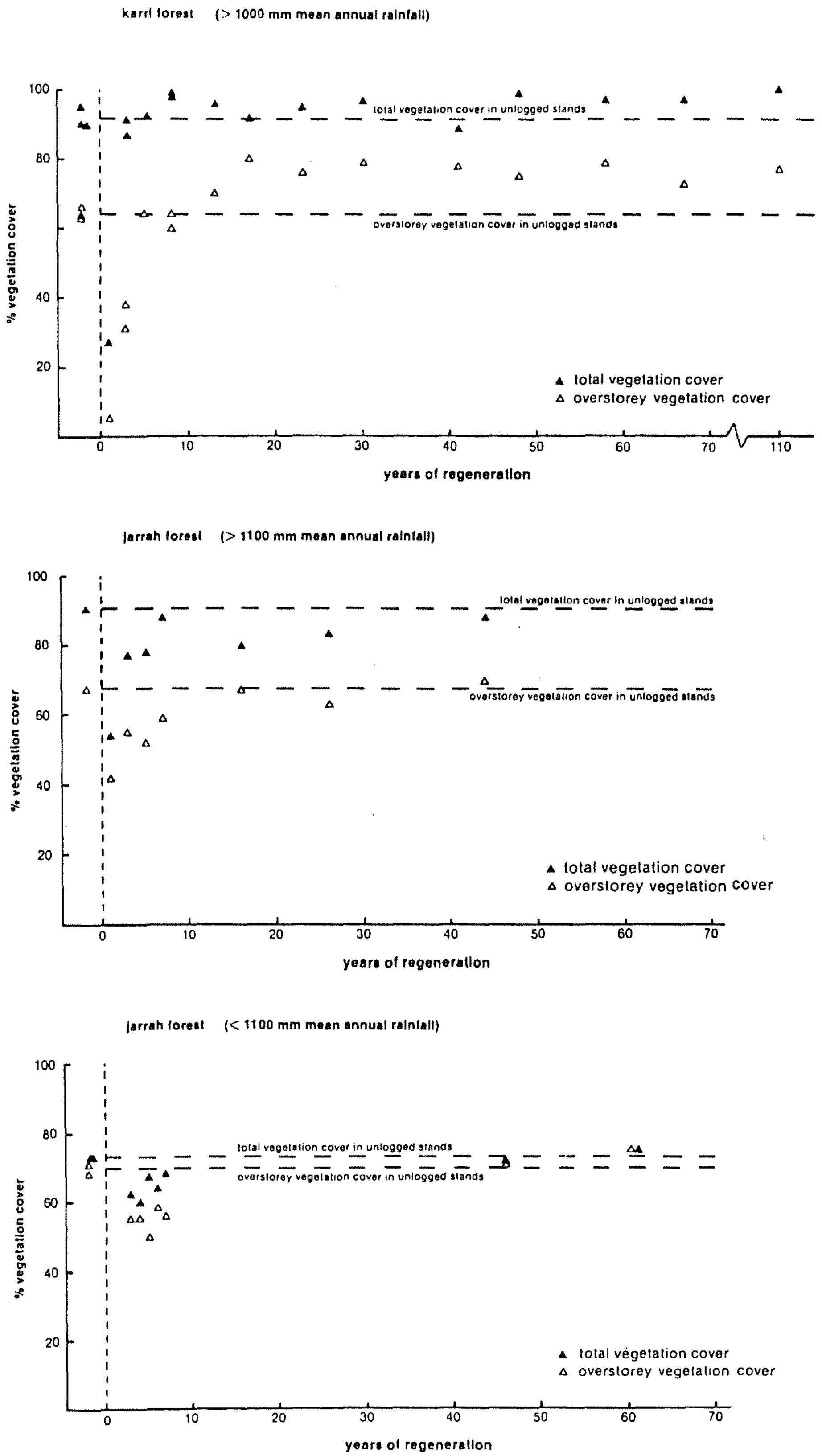


Figure 13 Regeneration of forest cover after logging (after Steering Committee, 1987)

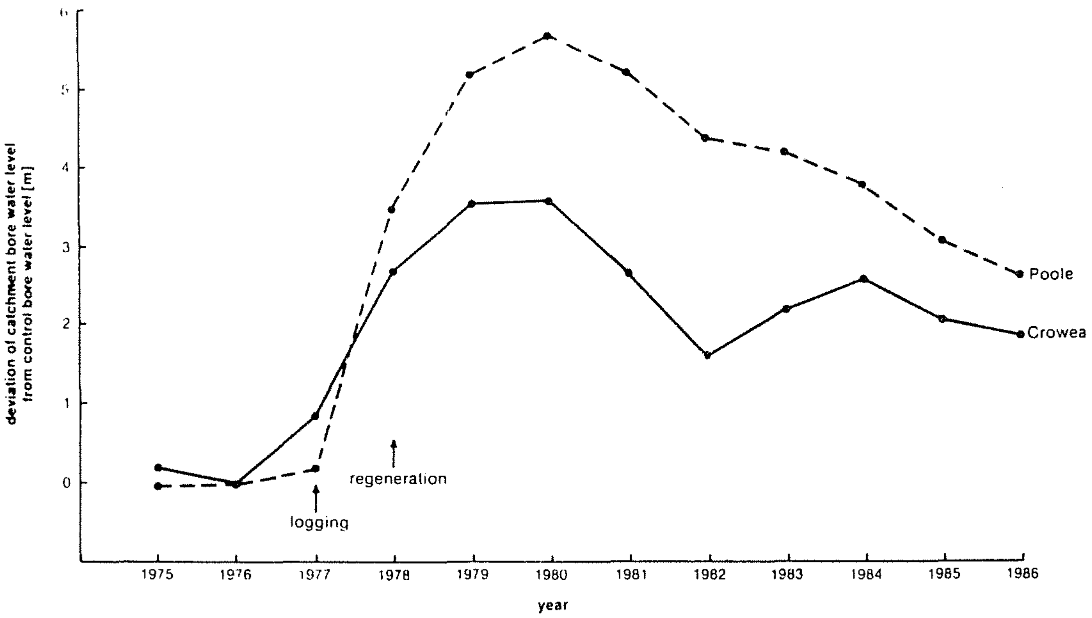


Figure 14 Change in minimum groundwater level relative to control bores following logging in two experimental coupes (after Steering Committee, 1987a)

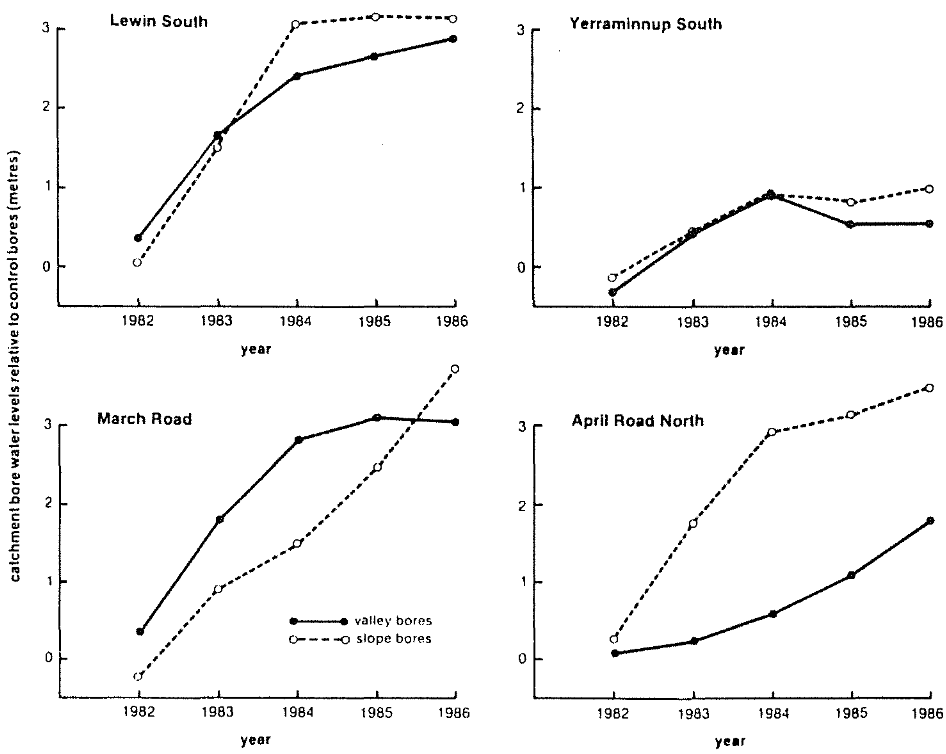


Figure 15 Changes in treated catchment bore water levels relative to control bores since logging (after Steering Committee, 1987a)

3.4.2 Stream salinity responses

Small increases in annual flow-weighted stream salinities of between 50 and 150 mg L^{-1} Total Soluble Salts (TSS) occurred on most treated experimental areas. However all annual flow-weighted salinities remained below 500 mg L^{-1} TSS. 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 (Fig. 16). The largest increase in annual flow-weighted salinities (approximately 150 mg L^{-1} TSS) occurred on a clearfelled catchment (March Road) in the intermediate rainfall zone (900-1100 mm yr^{-1}) which did not have a stream vegetation buffer. Salinity during periods of low flow on this catchment increased from 700 mg L^{-1} pre-logging to more than 1500 mg L^{-1} post-logging.

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 yr^{-1}) 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 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

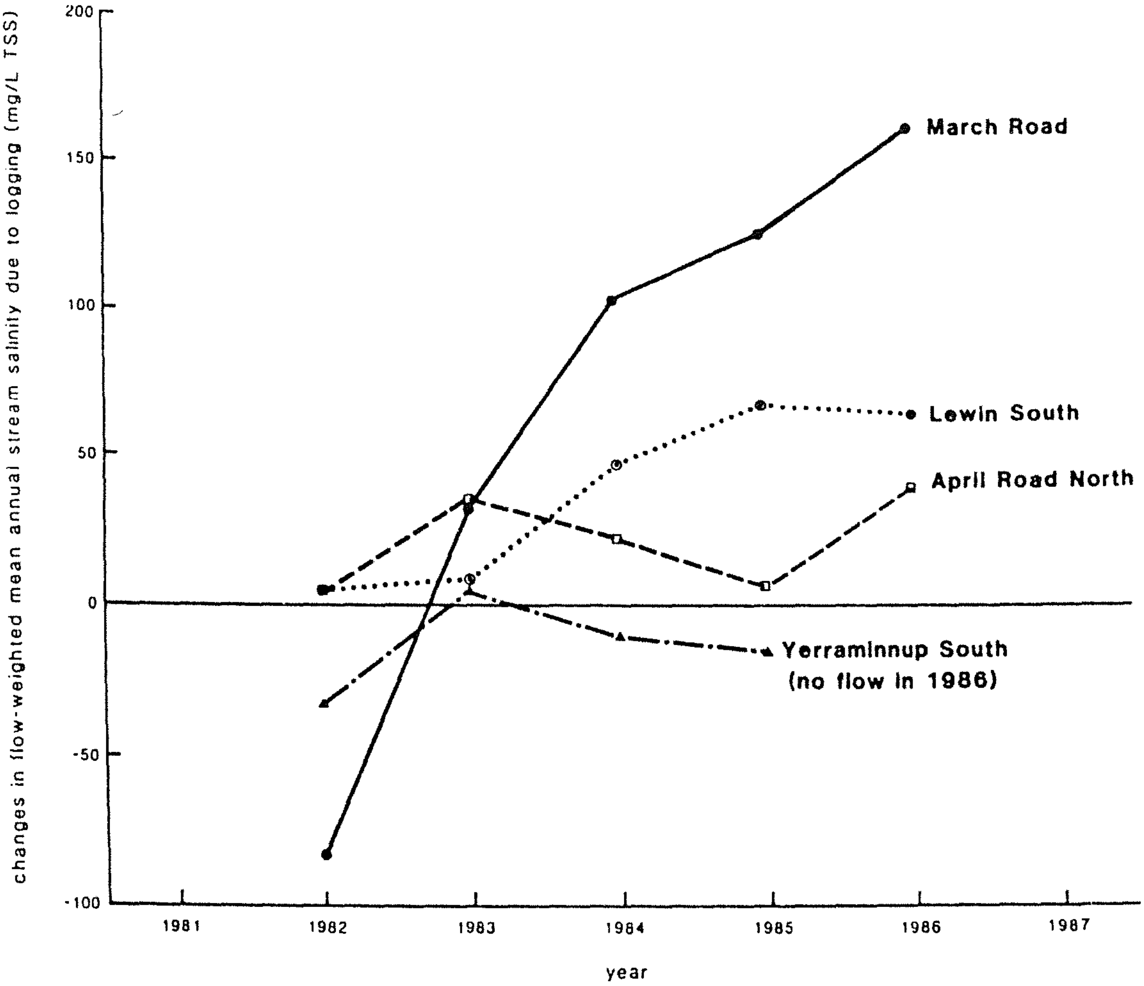


Figure 16 Changes in flow-weighted mean annual stream salinity in the four cut-over research catchments due to logging (after Borg et al., 1987a)

low flow salinities measured at greater than 1500 mg L^{-1}, 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.

3.4.3 Sediment concentrations

Stream sediment concentrations prior to logging were less than 5 mg L^{-1} 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 (Fig. 17). 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^{-1} and 20 mg L^{-1}. 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 (Fig. 12). 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.

3.4.4 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 (Fig. 18). 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

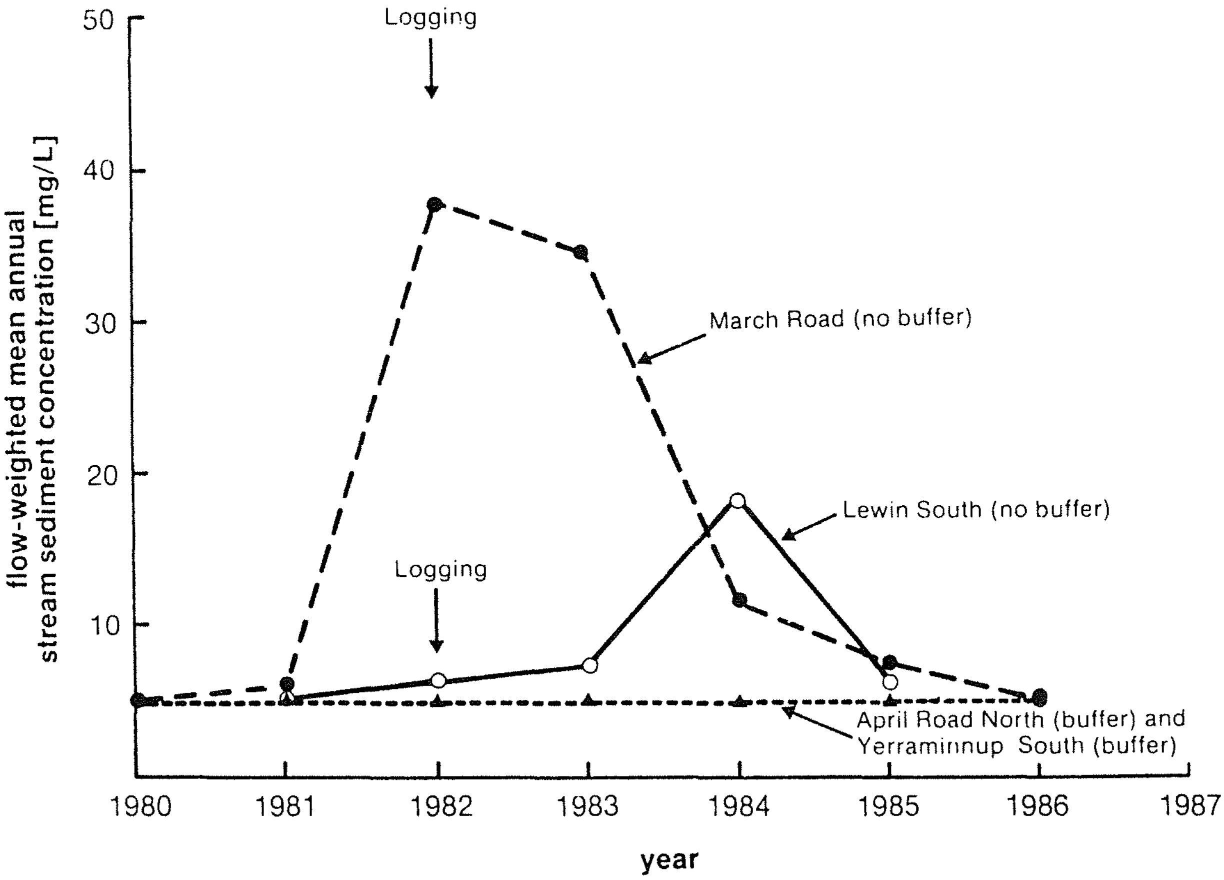


Figure 17 Changes in flow-weighted mean annual stream sediment concentration following logging (after Steering Committee, 1987a)

(Fig. 19). If all stands were subsequently left unthinned, a significant reduction in water yield could result in the longer term.

3.5 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 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;

(iii) improvement in scheduling of logging and road construction to further limit winter operations in the most sensitive areas;

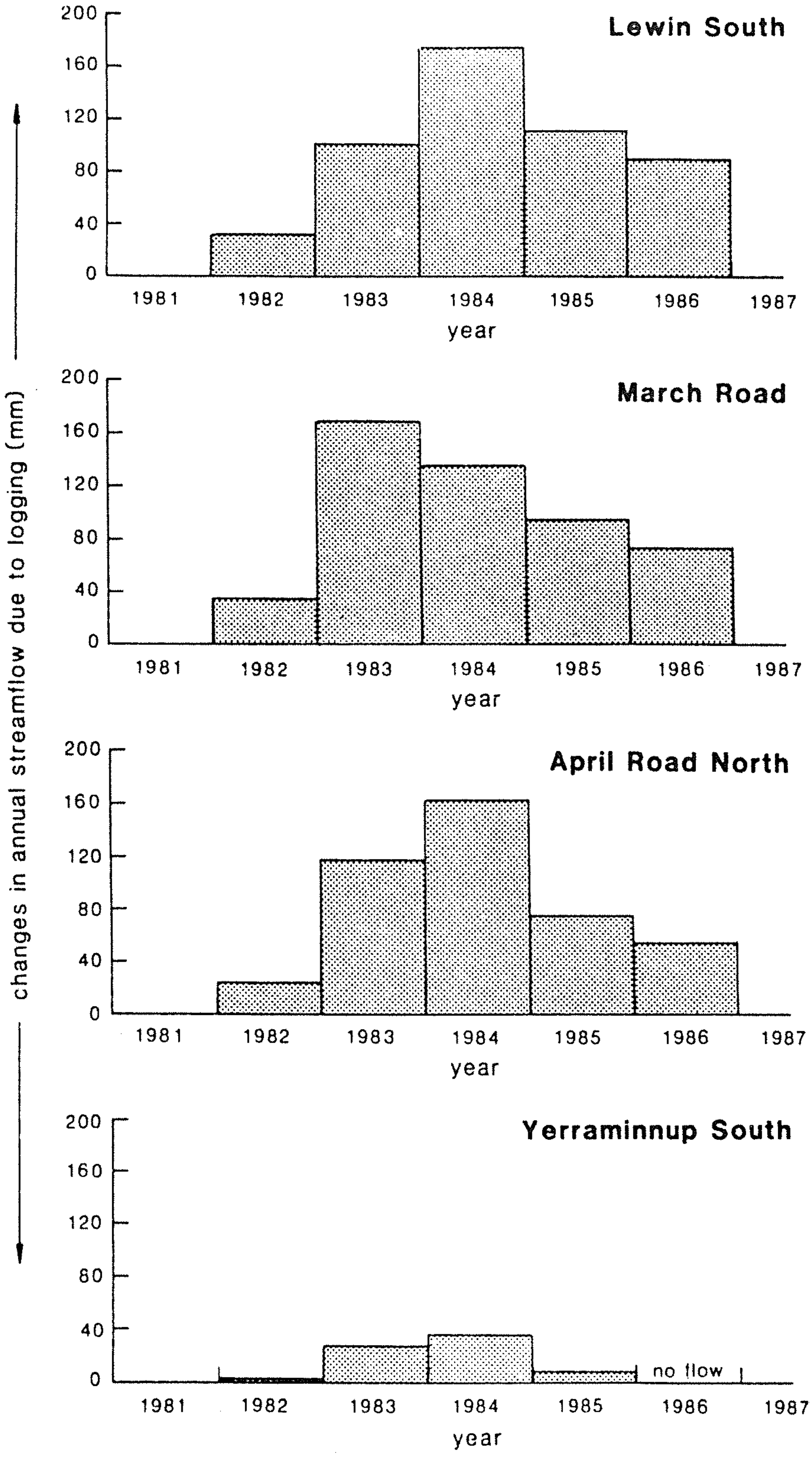


Figure 18 Changes in annual streamflow in the four cut-over research catchments due to logging (after Borg et al., 1987a)

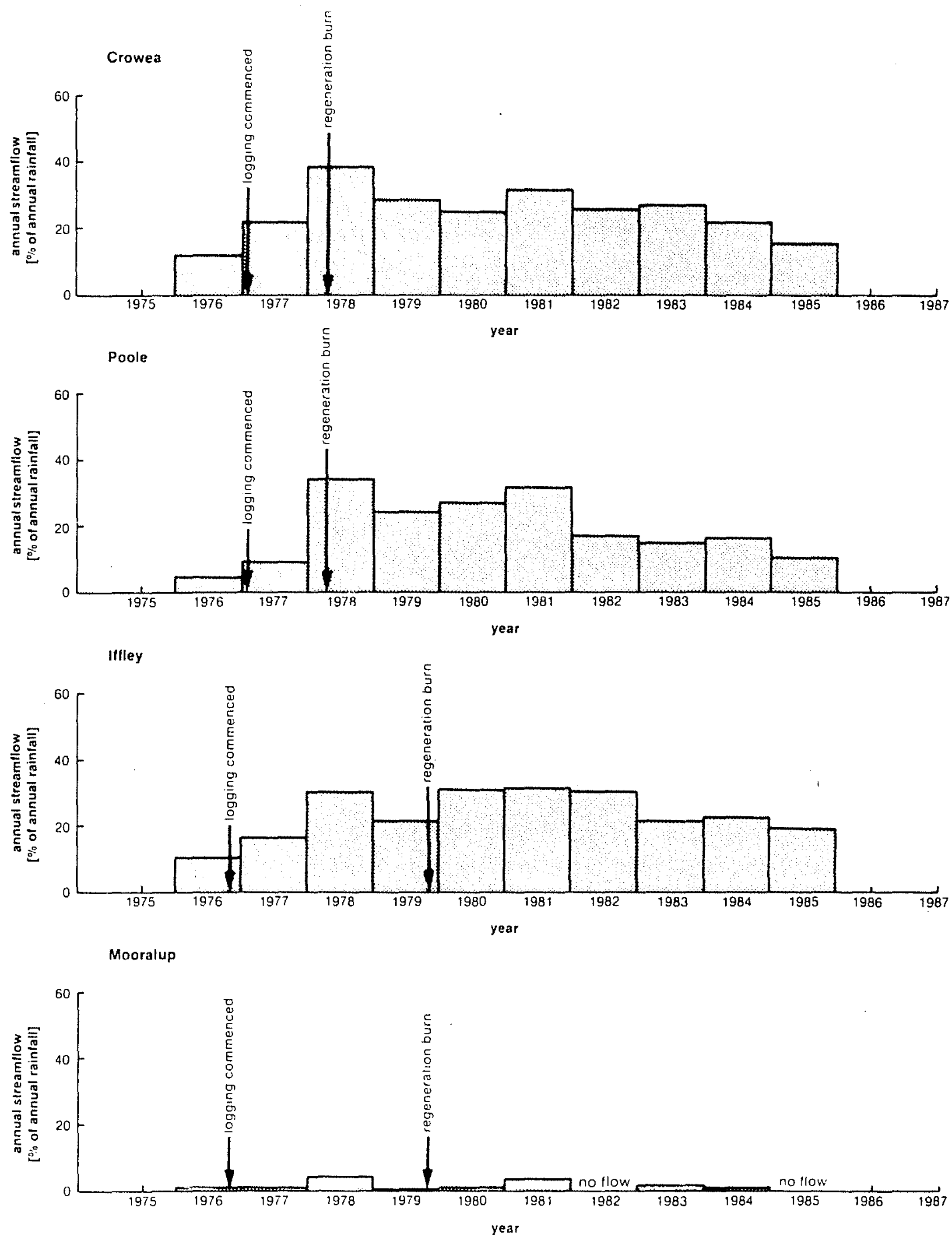


Figure 19 Annual streamflow in the four experimental coupes (after Steering Committee, 1987a)

(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.

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).

3.6 Conclusions

- 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.

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

- 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.

- The long term effects of regeneration on stream yield remain to be evaluated.

4. EFFECTS OF CLIMATIC CHANGE ON STREAM YIELD AND SALINITY OF FOREST CATCHMENTS

4.1 Introduction

Global climatic change associated with the Greenhouse Effect may have a significant impact on water resources in forested areas of south-western Australia. The main factors likely to affect stream yield are changing rainfall, temperature, humidity and carbon dioxide. Evidence for change in these factors and a brief discussion of their likely impacts are discussed below.

4.2 Rainfall Predictions and Trends this Century

4.2.1 Rainfall predictions for the Greenhouse Effect

Regional rainfall forecasts have the greatest uncertainty of all the major climatic variables. Current predictions of the rainfall changes in this region derive essentially from the expected polewards movement of the atmospheric high pressure belt from the desert latitudes. As a result the winter depressions and cold fronts, which bring rain to the south west, will pass further south, penetrating the region less frequently and possibly with reduced intensity. Based on global climatic models and trends this century, it is predicted that winter rains will decrease by 20% or more (Pearman, 1988) over the next 50 years. These figures and the timing of the start of the decline are, however, highly uncertain.

A contrary scenario assumes that, along with the poleward shift in the westerlies and associated rainfall belt, there would be an increase in the number of 'cut-off' lows produced as a result of a more split flow pattern in the upper winds over the Australian region in winter. This scenario would lead to an increase of up to 40% in summer rainfall in the south-west and also a slight increase in winter. The rainfall predictions for the two scenarios are illustrated in Fig. 20.

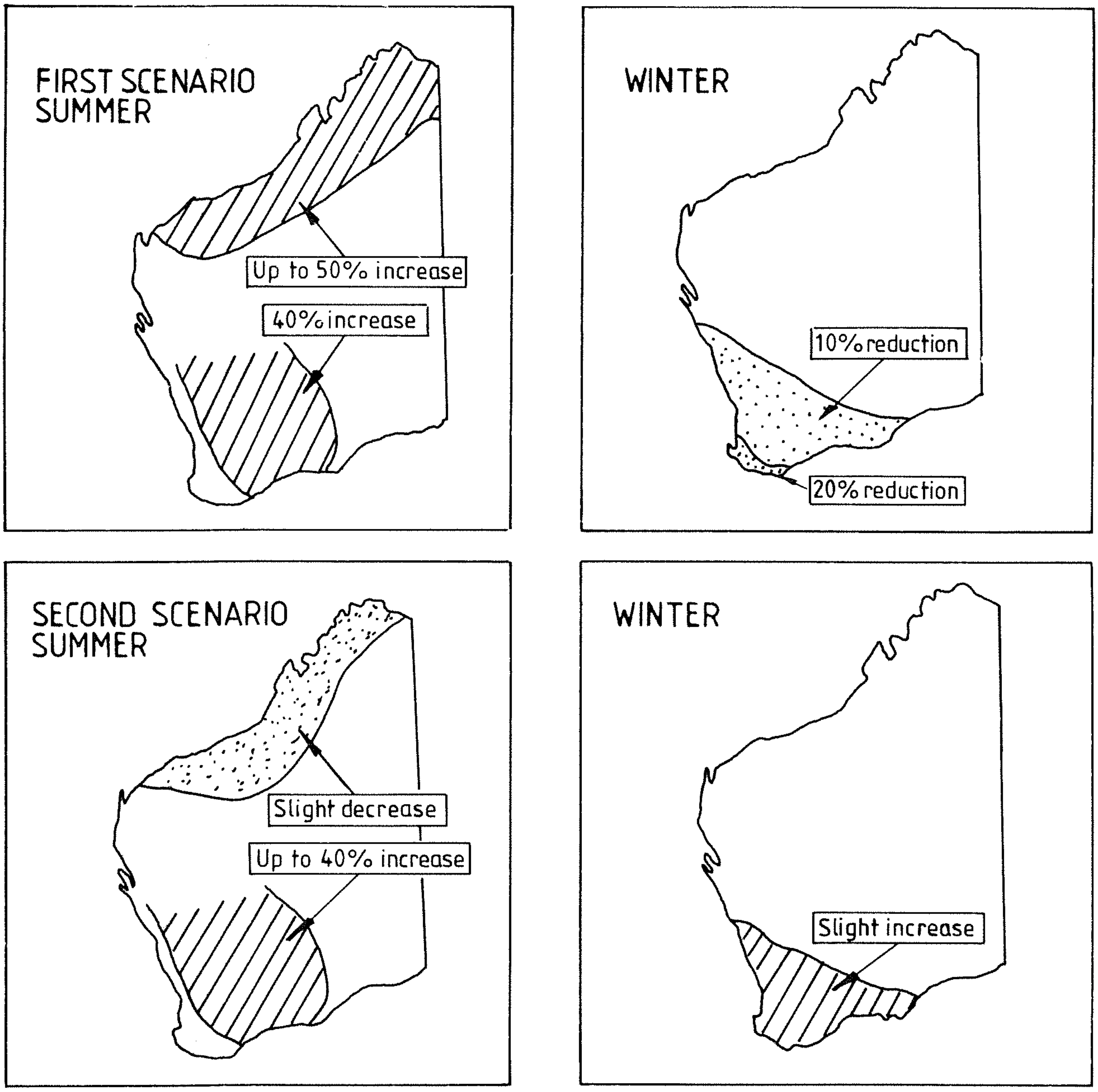


Figure 20 Two opposing scenarios for rainfall change due to the Greenhouse Effect over the next 50 years (after Hille, 1989)

4.2.2 Rainfall trends this century

Reliable areal rainfall records commenced in south-west Western Australia in the 1890s. Winter rainfall is the most relevant to streamflow and stream salinity since nearly all summer rainfall is evapotranspired. Rainfall regions of the south-west are shown in Fig. 21. This figure also shows rainfall changes for the months June-August across the south-west, expressed as percent per decade over the period 1913-86. Statistically significant decreases occur in all the south-western areas (8, 9, 9A, 10, 10A). The inland drier areas are suggestive of increases but most are not significant. The apparently significant upward trend in the district around Kalgoorlie may be due to inhomogeneities in the data, especially as there are only a few stations in the district.

Time trends in winter (May-October) rainfall from the 1890s for the two most south-western regions (9A and 10A) are shown in Figs. 22 and 23. In both cases the 5 year moving averages and long term split regressions (Broadbridge, 1988) are strongly indicative of declining rainfall from around 1940. The rates of rainfall decrease on the basis of the regressions are about 3 mm yr^{-1} (9A) and 1.85 mm yr^{-1} (10A) with predicted total decreases over the period 1945-1990 of about 125 mm (17%) for 9A and 75 mm (19%) for 10A.

The annual distribution of rainfall for region 9 (Fig. 24) for the periods 1913-45 and 1946-78, shows that most of the rainfall decrease has occurred during the winter months from May to September, with decreases of 22% in August and 30% in September. The monthly rainfall frequency distributions for August in the two periods (Fig. 25) is suggestive of a real shift in the whole distribution rather than a change brought about by a few extreme events.

From the data presented above, it appears that a significant decline in rainfall in the south-west has occurred gradually since the 1940s. Although this trend appears to be real it may not necessarily be associated with the Greenhouse Effect.

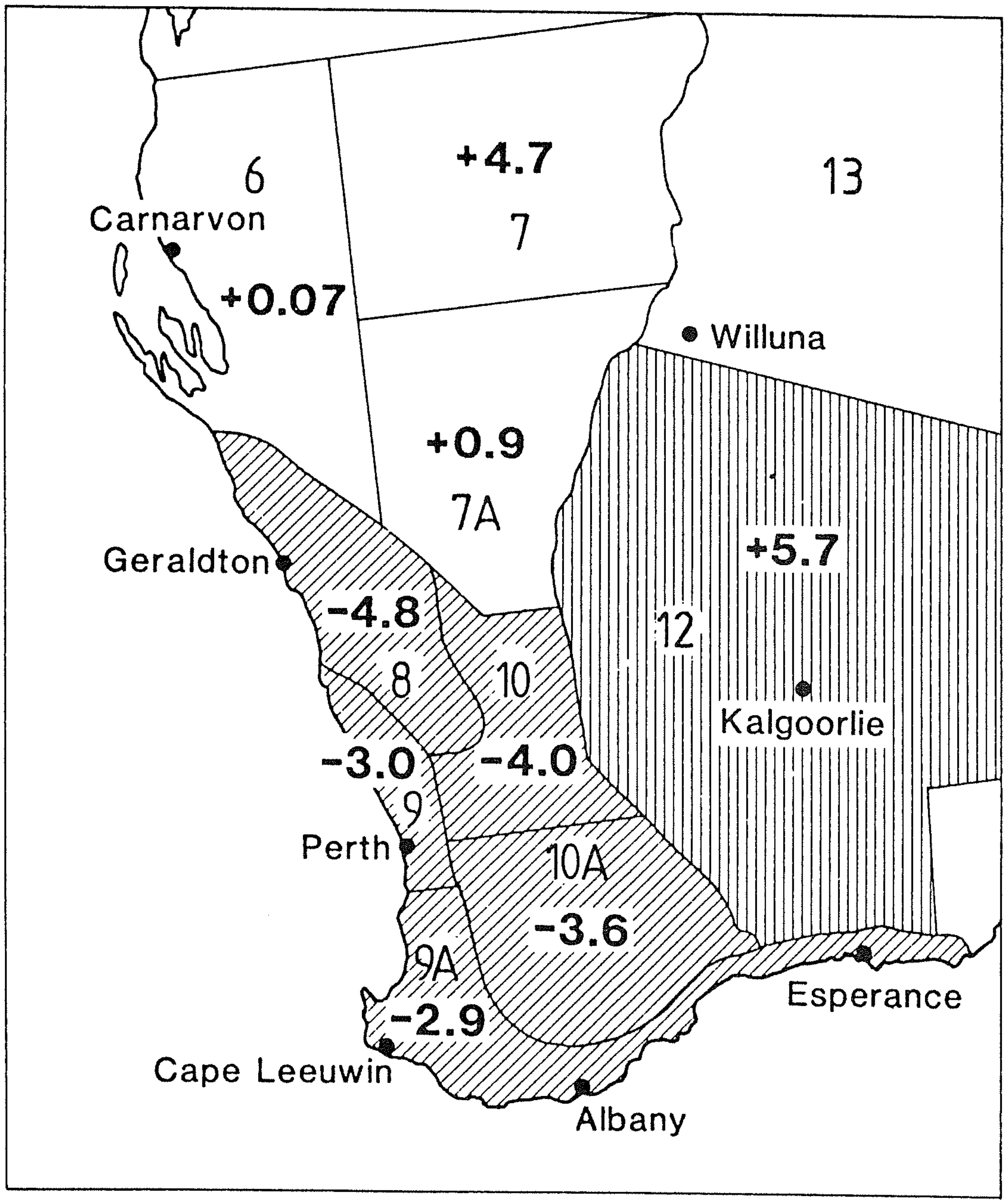


Figure 21 Trends in winter (JJA) rainfall in percent per decade, over the period 1913-86, for various districts in the south-west of Western Australia. Shading indicates trends which are statistically significant at the 95% confidence level using the Mann-Kendall rank test (adapted from Pittock, 1988)

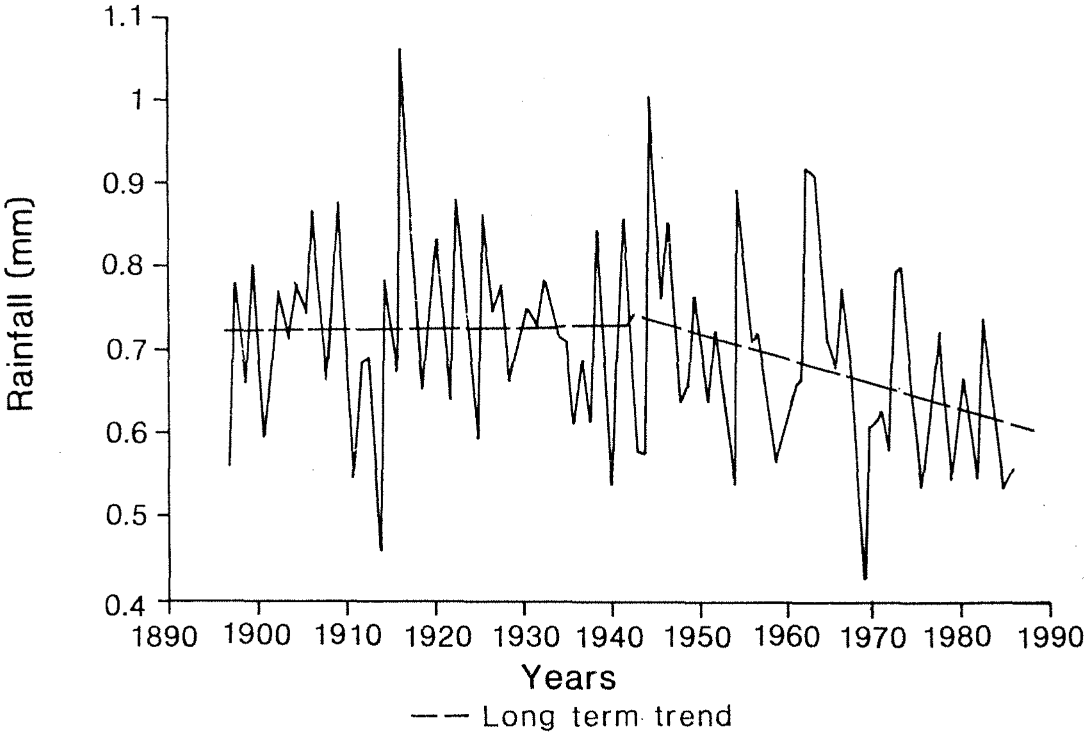


Figure 22 Winter (May-October) rainfall variation for district 9A for period 1897-1986 (after Broadbridge, 1988)

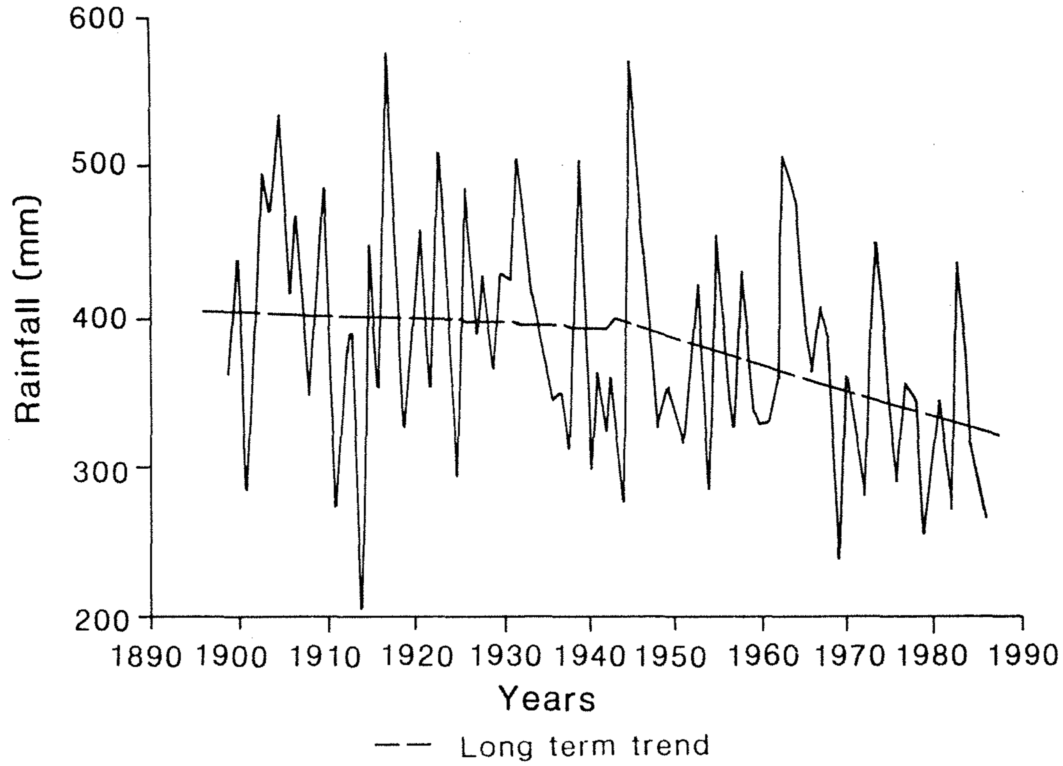


Figure 23 Winter (May-October) rainfall variation for district 10A for period 1897-1986 (after Broadbridge, 1988)

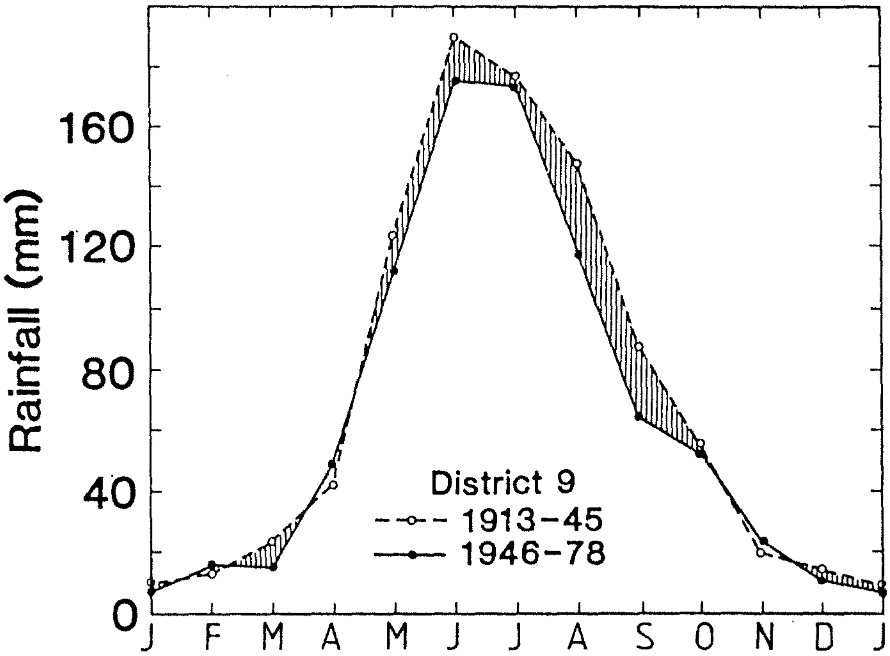


Figure 24 Mean annual cycles of rainfall in the intervals 1913-45 (dashed lines) and 1946-78 (full lines) for district 9 near Perth, W.A.

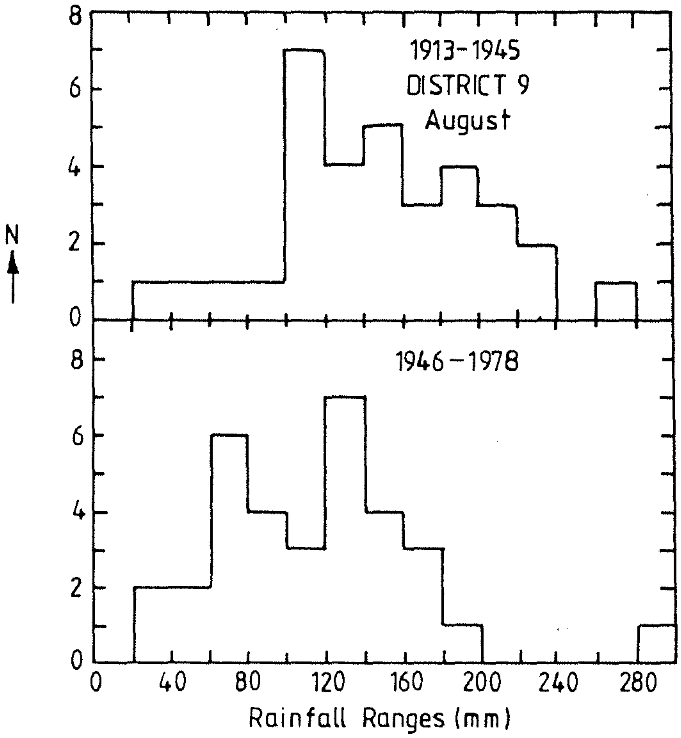


Figure 25 Frequency distributions of August precipitation in district 9 for the two data intervals 1913-45 (upper graph) and 1946-78 (lower graph) (after Pittock, 1983)

4.3 Effect of Rainfall Change on Forest Stream Yield

The impact of the Greenhouse Effect on stream yield is likely to be a complex biophysical interaction involving changes in rainfall, temperature, humidity and CO_2. Effects due to rainfall change alone are considered in this section, under the assumption of the first scenario of a 20% rainfall decrease.

A preliminary assessment of possible decreases in streamflow were made using a simple statistical relationship derived from historical rainfall and streamflow data for 14 streams in the region with a period of record from 1911 to 1980 (Sadler et al., 1988). The relationship between mean annual flow (Q) and annual rain (R) was assumed to have the form:

$$Q^x = a + b*R^y$$

where x and y were chosen such that Q^x and R^y had zero coefficients of skewness, and where a and b were chosen by linear regression. A strong linear relation was observed at all of the 14 sites studied.

The foregoing relation was used to assess annual streamflows, firstly with recorded rainfalls to represent stable climatic conditions and then assuming a gradual 20% reduction in rainfall from 1911 to 1980 to represent climate change. This indicated a corresponding decline of some 45% in mean annual streamflow.

The monthly flows of the historical record were then reduced in proportion to the calculated annual decrease for use in a multi-reservoir, monthly water balance simulation program for the determination of water supply system yield. This led to a predicted 40% reduction in water supply yield.

4.4 Effect of Rainfall Decrease on Forest Stream Salinities

The likely impact of a drying climate on forest stream salinities can be assessed by analysing stream salinity trends since 1940 and over the last decade (1976-86) when rainfall has been declining. The results of this analysis (Table 3) show that all (except one) forest streams have a trend of decreasing stream salinity. Examples of the salinity trend of catchments with the longest data record in high (>1100 mm yr^{-1}), intermediate (900-1100 mm yr^{-1}) and low (<900 mm yr^{-1}) rainfall zones are shown in Fig. 26.

The North Dandalup River (1300 mm yr^{-1} rainfall) has a period of record from 1939-86. Over this time the stream has been fresh with relatively low annual salinity variability (mean = 185 mg L^{-1}, standard deviation S.D. = 36 mg L^{-1}, coefficient of variation C.V. = 19%). There has been a marked downward trend in stream salinity of 1.5 mg L^{-1} yr^{-1} over the period 1939-86 which is significant at the 0.01% level. The rate of decrease in annual salinity has accelerated in recent times, averaging 7.4 mg L^{-1} yr^{-1} over the period 1976-86.

Yarragil Brook catchment (1050 mm yr^{-1} rainfall) has the longest record (1951-86) of all intermediate rainfall zone catchments. Its stream salinity is higher and more variable than the high rainfall zone catchment (mean = 389 mg L^{-1}, S.D. = 1230 mg L^{-1}, C.V. = 31%). Stream salinity in this catchment has declined at an average rate of 7.7 mg L^{-1} yr^{-1} over the period of record and has a current (1976-86) rate of decrease of 16 mg L^{-1} yr^{-1}.

In lower rainfall areas there are very few fully forested catchments. The Canning River (station 616065), with the longest period of record (1968-86), has a mean stream salinity of 293 mg L^{-1} (S.D. = 132 mg L^{-1}, C.V. = 45%). The average rate of decline in stream salinity over the whole period was 17 mg L^{-1} yr^{-1} while its rate of decline over the period 1976-86 was 13 mg L^{-1} yr^{-1}.

It is evident that significant stream salinity reductions have been occurring on forested catchments over the last 20 years or so. The main reason for this is considered to be the general decline in groundwater level in response to generally lower rainfall conditions. A clear example of this is shown in Fig. 27 for Bee Farm Road catchment, where groundwater close to the

Table 3: Stream salinity trends of fully forested catchments

Catchment	NGSN	Area (km²)	Period of record	Annual rainfall (mm)	Annual stream salinity (mg/L)	Period of record salinity trend (mg/L/yr)	Stat. sig.	Current salinity trend (1976–86) (mg/L/yr)	Stat.[(1)] sig.
Carey Bk	608002	40.6	75–86	1420	116	+0.1	0.78	-0.1	0.69
Nth Dandalup R	614016	153	39–86	1300	185	-1.5	0.0001	-7.4	0.01
Little Dandalup R	614233	396	67–86	1300	138	-3.7	0.0001	-4.5	0.01
Harvey R	613002	148	70–86	1250	114	-2.0	0.002	-2.2	0.02
Stones Bk	612005	14.7	72–86	1220	181	-0.6	0.86	-3.7	0.44
Barlee Bk	608001/048	164	62–86	1170	152	-0.2	0.82	-2.8	0.42
Yarragil Bk	614044	72.5	51–86	1075	389	-7.7	0.0001	-16.3	0.01
April Rd North	607012	2.1	76–86	1070	122	-1.9	0.19	-1.9	0.19
Harris R	612036/017	383	52–86	1000	224	-8.0	0.03	-5.4	0.41
Deep R	606001	458	75–86	990	184	3.5	0.28	+4.9	0.20
Little Darkin R	616010	40.1	67–86	900	390	-25.9	0.0009	-19.7	0.23
Canning R (Glen Eagle)	616065	544	68–86	890	293	-17.0	0.0004	-12.6	0.11
Pickering Bk	616009	31.1	74–86	750	229	4.9	0.001	-12.1	0.01
Tunnel Rd	614011	2.07	75–86	730	285	-52	0.001	-47.2	0.003
Bee Farm Rd	614012	1.81	75–86	730	480	-106	0.008	-128 [(3)]	0.0092
Chalk Bk	614123	104	59–86	700	293	-5.0	0.02	-11.7	0.003
Yarra Rd[(2)]	616017	6.3	74–82	680	90	-8.3	0.08	-7.1	0.23

(1) Statistical significance is based on the F-test, where value denotes level of significance. For example 0.70 means that the observed trend has a 70% chance of being zero (non-existent).

(2) Current salinity trend for Yarra Rd is from 1976 to 1982 due to closure of station in mid 1983.

(3) No flow recorded from 1984 onwards

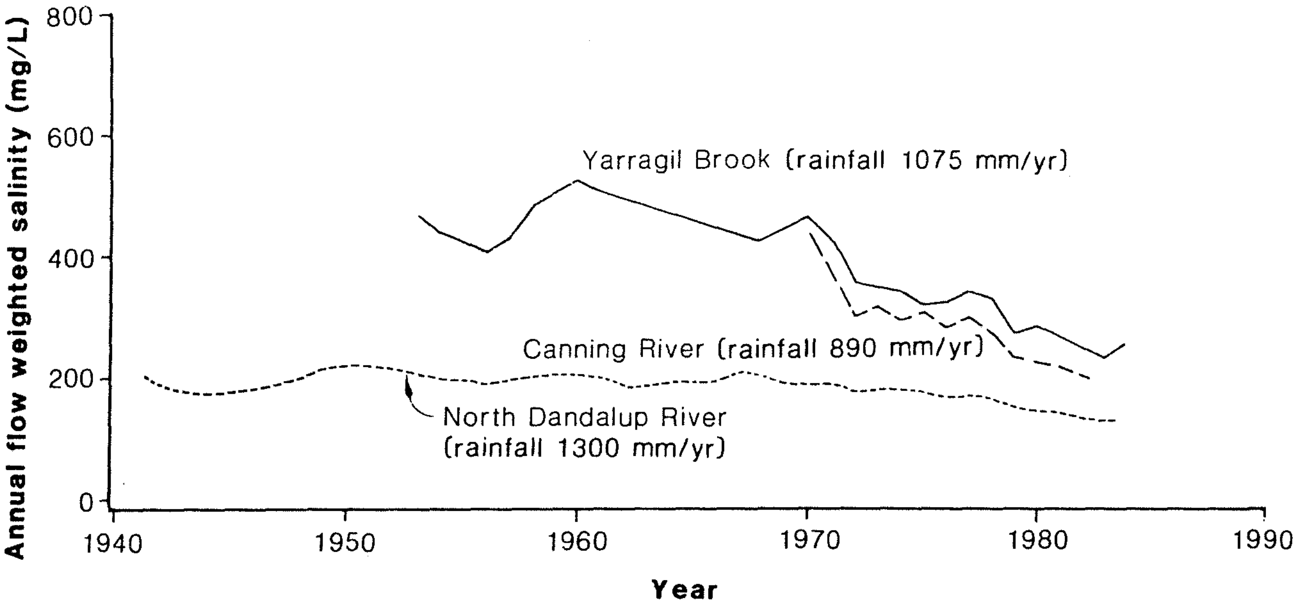


Figure 26 Stream salinity trends for forested catchments in high, intermediate and low rainfall zones (after Schofield et al., 1988)

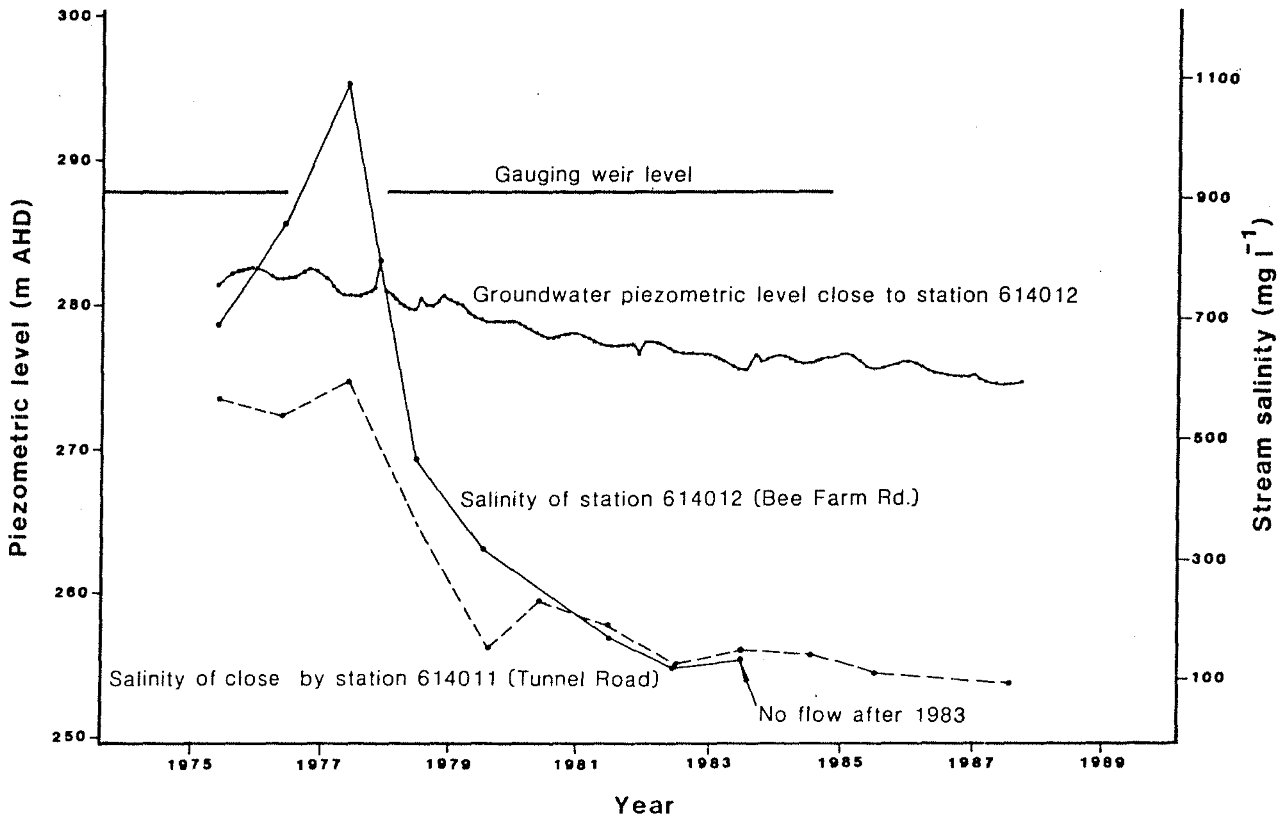


Figure 27 Response of stream salinity to decreasing groundwater levels (after Schofield et al., 1988)

gauging station fell 4.4 m from 1976 to 1981. Over the same period the annual stream salinity declined at an average rate of 128 mg L^{-1} yr^{-1}. The rainfall for the period was 10% below the long term average. The decline in groundwater would mean a decrease in salt contribution to streams both directly as groundwater flow and indirectly as salt movement to the surface soil layers during summer and subsequent leaching to streams during winter.

4.5 Effects of Increasing Temperature

Most climate models indicate an increase in global temperature resulting from increasing 'greenhouse gases' and indeed there is strong evidence that temperature increases are already occurring (Karoly, 1988). In Western Australia temperature increases of up to 5.6°C over the next 50 years have been predicted (Hille, 1989). With other factors constant, increasing temperature will lead to increasing evaporation and decreased stream yield. Application of the Penman equation to local (Perth) conditions indicates that potential evaporation will increase at the rate of 1.5% per °C.

4.6 Effects of Increasing CO_2

The fact that the concentration of CO_2 in the atmosphere is increasing is now well established (Pearman, 1988). Over Australia CO_2 is increasing at a rate of 0.4% yr^{-1} (Fig. 28). Analyses of air entrapped in the Antarctic ice sheet show that pre-industrial and pre-agricultural levels of CO_2 were about 23% lower than in 1987 (Fig. 29).

A number of studies have shown that the stomatal resistance of plants is increased when CO_2 is increased. For example Wong (1980) showed that the stomatal resistance of E. pauciflora was 1 s cm^{-1} and 3.4 s cm^{-1} when grown under CO_2 concentrations of 330 and 660 ppm respectively and under low nitrogen levels.

The effect of increased stomatal resistance is decreased transpiration and increased streamflow. The quantitative impact

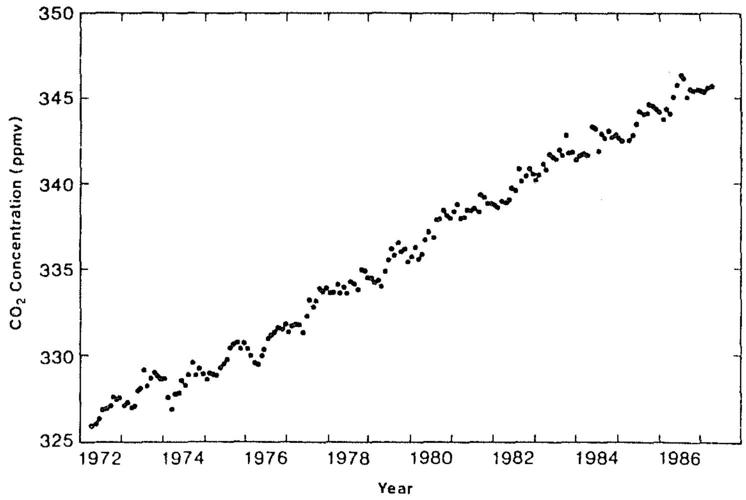


Figure 28 Atmospheric CO_2 measured in the mid troposphere over south eastern Australia (after Pearman, 1988)

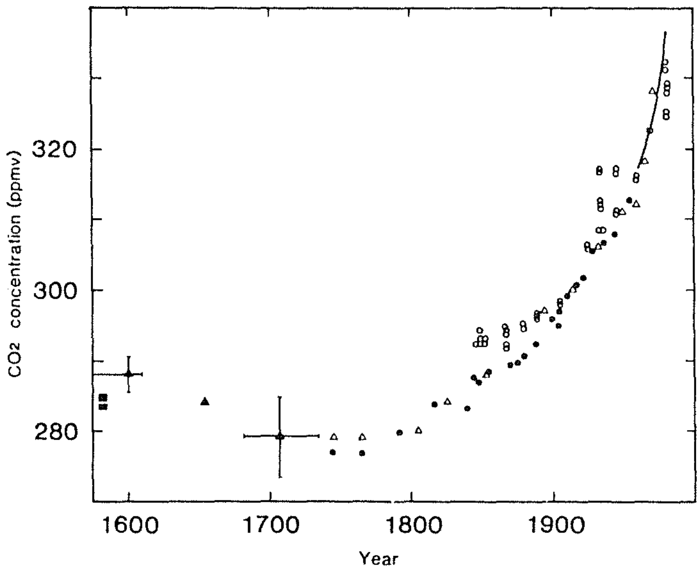


Figure 29 The changes of atmospheric CO_2 concentration for the past few centuries as revealed in air extracted from Antarctic ice. Data are from the following sources : ■ and ●, Friedli et al. (1984) and (1986) respectively; Δ , Neftel et al. (1985); ▲ Etheridge et al. (1987), horizontal bars represent the range of gas ages of the samples, vertical bars are the 1 sigma limits of the data represented by the mean; o, unpublished data from G I Pearman and D Etheridge (Australian Antartic Division). Full line represents modern Antarctic measurements (Bacastow and Keeling, 1981; Komhyr et al., 1985) (after Pearman, 1988)

on streamflow was assessed with a catchment hydrological model by Aston (1984). In his study, an assumed doubling of stomatal resistance (from a doubling in CO_2 concentration) led to an increase in stream yield of a small (5 ha) catchment of 85% and a large (417 km^2) water supply catchment of 40-90% depending on assumptions. A similar result was obtained from the modelling of 12 catchments in Arizona (Idso and Brazel, 1984) who showed that under a climate change involving a 2% rise in temperature, 10% drop in precipitation and a doubling in CO_2 concentration, there would be an average 42% increase in streamflow.

A secondary hydrological effect of CO_2 increase is increased plant growth. Although leaf area increases can be substantial under a doubling of CO_2, such increases are not expected when nutrients are limiting (Wong, 1980). Nutrient limiting conditions would generally prevail in the forest water catchments of south-west Western Australia.

In summary, therefore, the strong reductions (45%) in stream yield predicted for a 20% decrease in rainfall may be entirely offset by the antitranspirant effect of increased CO_2.

PART II RECLAMATION AND ENHANCEMENT OF WATER RESOURCES USING FORESTRY

5. REFORESTATION FOR SALINITY CONTROL

Research to develop appropriate strategies of partial reforestation for salinity control has involved tree selection and establishment and an evaluation of the effects of a range of tree planting strategies on groundwater level and stream salinity.

5.1 Tree Selection

The initial criterion for tree selection is adaptation to the environment. In south-west Western Australia this includes adaptation to climate, soils, pests, diseases, fire, and in some locations waterlogging and salinity. Adaptation to a given site may vary with genus, species or provenance.

Only a few species have so far been identified which have provenances adapted to waterlogging and salinity (saline seep) conditions. These include *Casuarina obesa*, *Eucalyptus sargentii*, *E. camaldulensis* and *E. occidentalis*. These species can provide some secondary benefits in addition to salinity control but not sufficient to make them commercial propositions based on returns from their secondary benefits only.

Further progress in tree selection for salt/waterlogging conditions is expected from research into the identification, cloning and testing of potentially high salt/waterlogging tolerant trees (Bell and van der Moezel, 1989). Over the past four years, 100 species, 323 provenances and 16736 seedlings have been screened for salt/waterlogging tolerance. Of these 410 seedlings were selected for micropropagation reseach. Successfully micropropagated individuals are now available in *Eucalyptus*, *Melaleuca* and *Casuarina*, and clones of the first of these are being produced for field trials.

For well drained soils, away from saline seeps, a wide range of adapted species have been identified. Several are considered to have commercial potential. These include Pinus radiata for timber and other wood products and the fast growing eucalypts E. globulus, E. viminalis, E. botryoides and E. saligna for pulpwood production.

Having satisfied the adaptation criterion, the other two main criteria are water use and commercial value.

Knowledge of the water use capacity of various species for a range of conditions could allow trees to be selected to maximise the effectiveness of reforestation or minimise the area of agricultural land required for reforestation. Comparative water use, however, has been difficult to quantify accurately in the field (Borg and Giles, 1988).

The commercial value of species has been easier to determine and there are good data on some Eucalyptus and Pinus species. This is discussed further in section 5.4.

5.2 Tree Establishment

On well drained sites the following procedures give good establishment : ripping in late summer/autumn when soils are driest to give good break up; strip spraying of rip (planting) lines with a herbicide mix incorporating knock down and residual weed control ingredients; planting in June/July, followed by spot fertilising of each seedling with N and P fertiliser.

Saline seep sites are more difficult for tree establishment. Even with salt/waterlogging tolerant trees, reforestation techniques are still being developed (Ritson and Pettit, 1988). Ripping, followed by herbicide spraying of most sites (except salt scalded land) is usually necessary. However, fertilizing of seedlings may not be warranted (Ritson and Pettit, unpublished data). Ridge mounding is important. This reduces waterlogging stress by providing site drainage and an elevated planting position for seedlings above the water table. Double ridge mounds with seedlings planted in the trough between the ridges are more effective than single ridge mounds as the trough collects rain which facilitates salt leaching from the soil in the seedling root zone (Ritson and Pettit, 1989 a, b). Other techniques found to be effective in improving tree establishiment in saline seeps include the application of mulches such as hay to the mounds and increasing seedling container size (Ritson and Pettit, 1989c).

5.3 Evaluation of Reforestation Strategies

A number of experimental reforestation sites were established in the late 1970s (Fig. 30). The characteristics of these sites are summarised in Table 4. The sites have been evaluated in terms of their effectiveness in controlling salinity (Bell *et al.*; 1988, Schofield *et al.*, 1989). Timber, pulpwood and pasture production (in agroforestry layouts) were also evaluated but are not discussed further here.

5.3.1 Effect of reforestation strategy on groundwater level

Four partial reforestation strategies were tested : (A) lower slope and discharge zone planting; (B) wide-spaced plantations covering most of the cleared area; (C) strips or small blocks strategically placed but covering a small proportion of the cleared area; (D) dense plantations covering a high proportion (>50%) of the cleared area. In each strategy a component of lower slope and/or discharge zone planting was included. This was considered necessary if groundwater solute discharge to streams was to be eliminated.

(A) Lower slope and discharge zone planting strategy

Reforestation trials have been conducted at two sites using this strategy. Only one site, however, has sufficient data for interpretation. At this site, Stene's Valley Plantings (Fig. 31), 35% of the cleared area was replanted with *E. wandoo*, *E. rudis* and *E. camaldulensis* in 1979. The initial annual minimum

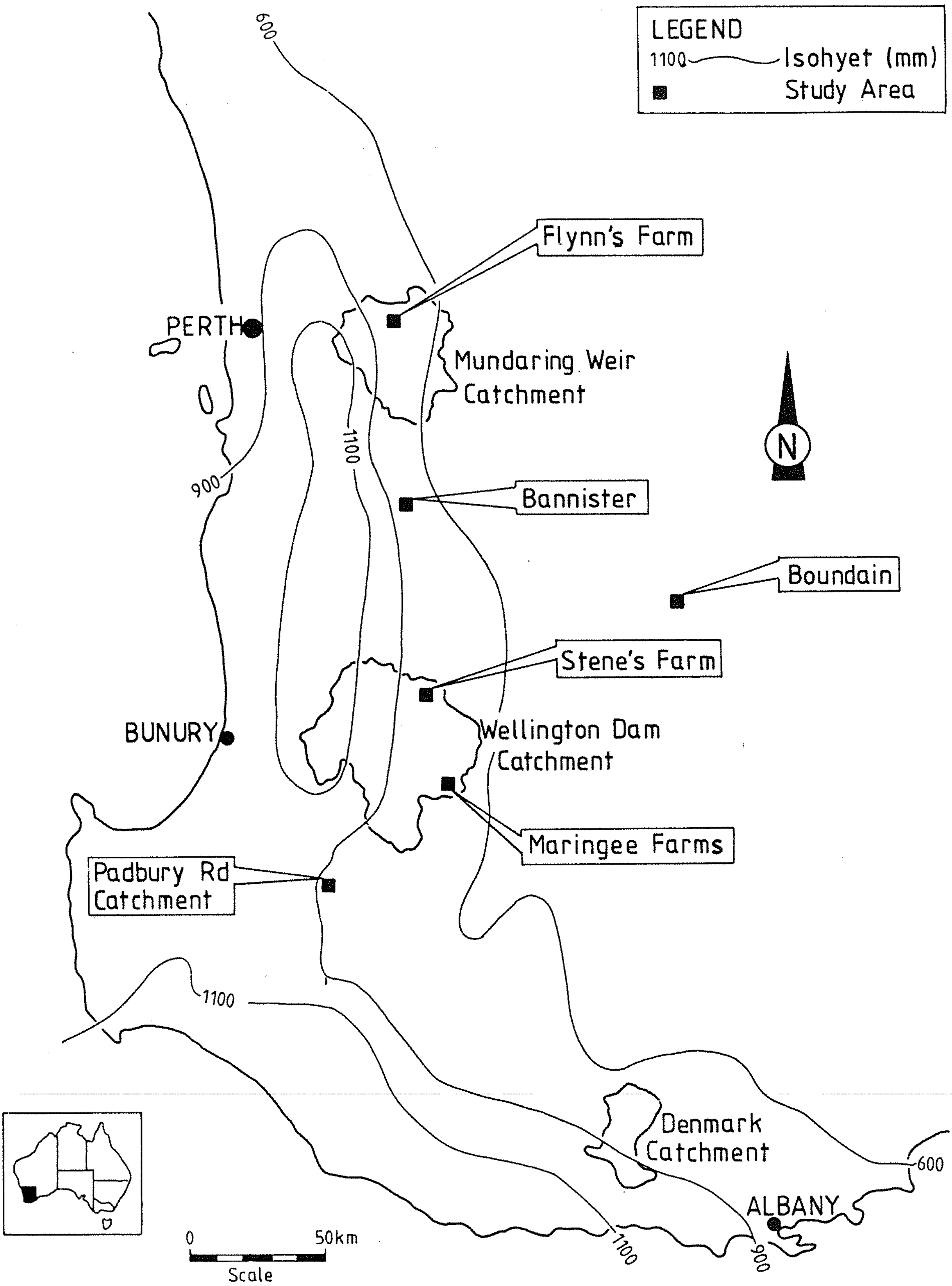


Figure 30 Location of reforestation study areas

Table 4: Characteristics of experimental reforestation sites

Site	Planting year	Main species planted	Proportion of site cleared (%)	Proportion of cleared area replanted (%)	Initial planting density (stems/ha)	Estimated stem density in 1986 (stems/ha)	Mean reforestation crown cover at Dec 1987 (%)	Initial* depth to water table (m)	Initial groundwater salinity (mg/L)	Depth of weathering (m)
Flynn's Farm										
Landscape	1977	*E. wandoo* *E. camaldulensis* *P. pinaster* *P. radiata*	98	8	670	500	43	2.1	4600	0-20
Hillslope	1978/ 1979	*E. camaldulensis* *E. wandoo*	100	54	1 200	1 000	29	3.3	7400	5-20
Agroforestry	1978	*P. radiata* *P. pinaster* *E. camaldulensis*	51	58	380/ 760/ 1 140	75/ 150/ 225	14	4.4	2400	3-13
Stene's Farm										
Strip Plantings	1976 to 1978	*E. camaldulensis* *P. radiata* *E. globulus* *P. pinaster* *E. wandoo*	31	14	1 200	600	47	2.7	7700	>20
Valley Plantings	1979	*E. wandoo* *E. rudis* *E. camaldulensis*	44	35	625	500	41	6.3	5400	>20
Agroforestry	1978	*E. camaldulensis* *E. sargentii* *E. wandoo*	25	57	1250	150/ 900	25	2.7	6600	>20
Arboretum	1979	63 *eucalypt* plus 2 pine species	35	70	625	0–600	39	7.1	5400	>20

* depth corresponds to the lowest groundwater level during the year.

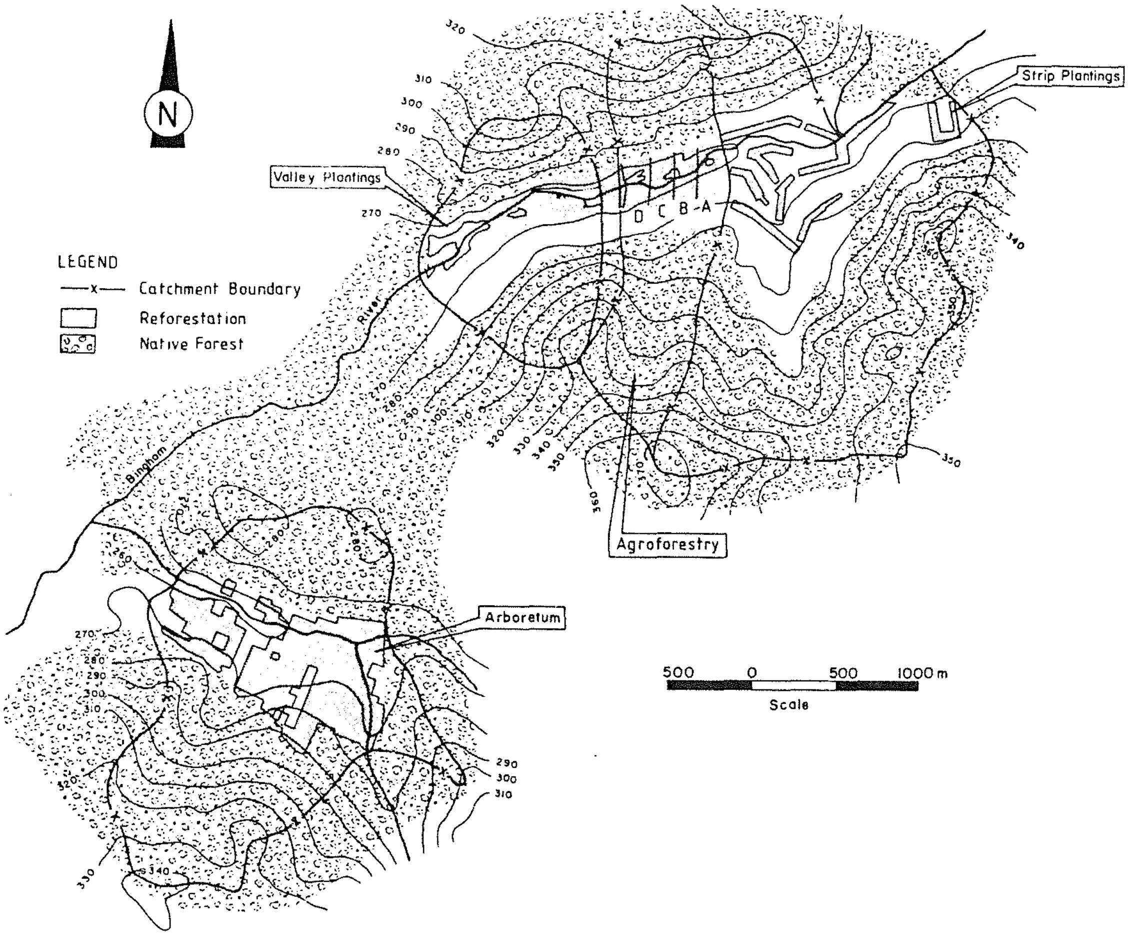


Figure 31 Stene's Farm experimental reforestation sites

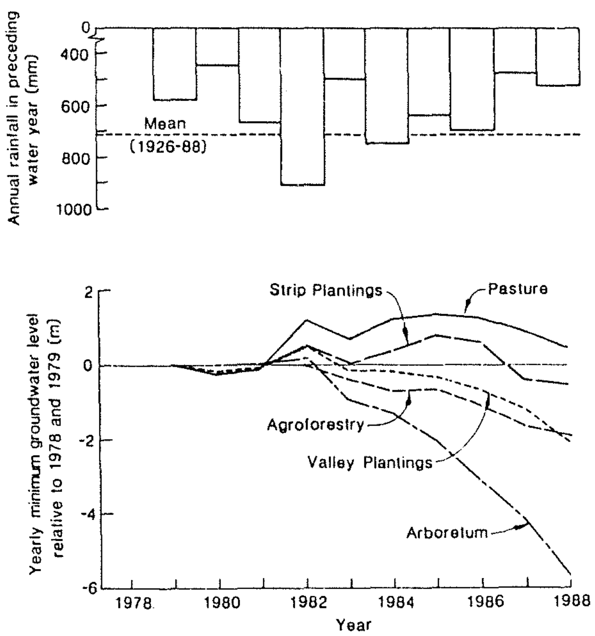


Figure 32 Annual rainfall and groundwater Level variations at Stene's Farm experimental reforestation sites (after Steering Committee, 1989)

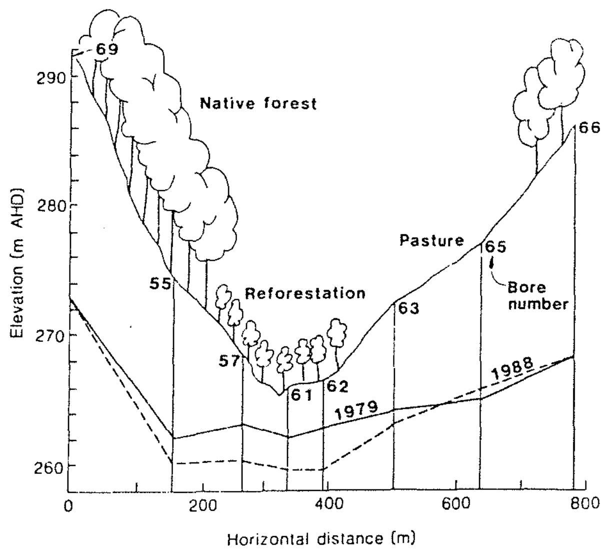


Figure 33 Comparison of annual minimum valley cross-section piezometric levels of 1979 1988 at Sten's Valley Plantings (after Steering Committee, 1989)

depth to groundwater beneath the plantation was 6.3 m and the initial groundwater salinity was 5400 mg L^{-1} TSS. Over the period 1979-88 there has been a lowering of the groundwater table beneath the reforestation of 2.0 m, whilst under pasture the groundwater level rose by 0.4 m (Fig. 32). The groundwater table responses beneath pasture, reforestation and native forest are shown by comparing valley cross-section potentiometric surfaces of 1979 and 1988 (Fig. 33). Over this period the groundwater levels have lowered beneath the reforestation but have risen slightly beneath the midslope pasture.

(B) Wide-spaced plantations

Reforestation in which trees are thinned to or planted at a wide spacing (low density), with pasture grazing between trees, has been investigated at Flynn's Agroforestry, Stene's Agroforestry and Boundain.

At Flynn's Agroforestry (Fig. 34), *Pinus radiata*, *P. pinaster* and *E. camaldulensis* were planted in 1978 and thinned between 1982 and 1985. The reforested area covered 58% of the cleared area. The initial yearly minimum depth to groundwater was 4.4 m and the average groundwater salinity was 2400 mg L^{-1} TSS. Over the period 1979-88 the groundwater levels beneath the reforestation declined by 1.2 m while over the same period groundwater under pasture at a nearby site decreased by 0.5 m (Fig. 35).

At Stene's Agroforestry (Fig. 31), *E. camaldulensis*, *E. sargentii* and *E. wandoo* were planted at a uniform density in 1978 and were thinned to differing densities in 1981. The reforested area covered 57% of the cleared area. The initial depth to groundwater was 2.7 m and the groundwater salinity was 6600 mg L^{-1} TSS. The groundwater level over the period 1982-88 averaged over the whole reforested area has shown a net decline of 1.8 m while under pasture at an adjacent site the groundwater level rose by 0.4 m (Fig. 32).

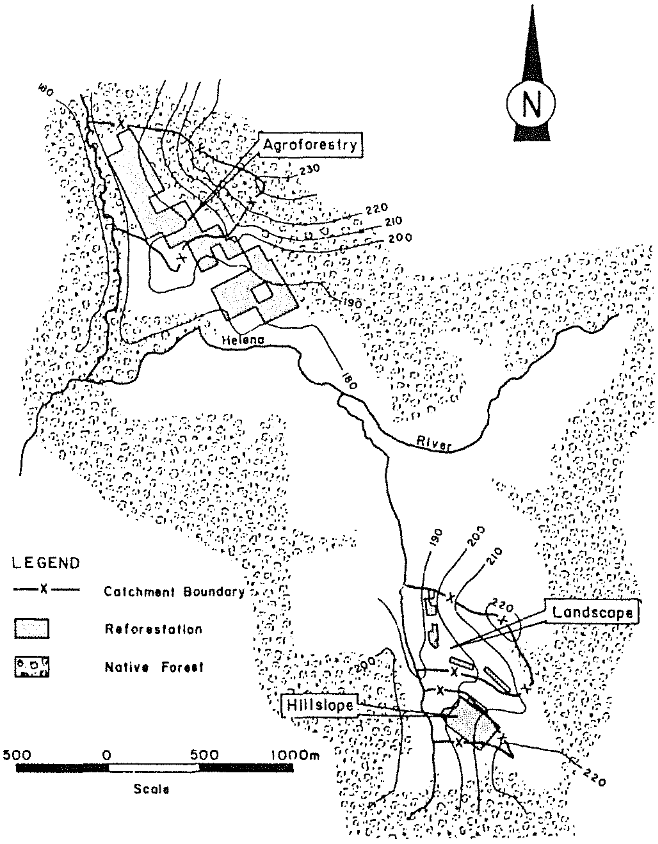


Figure 34 Flynn's Farm experimental reforestation sites

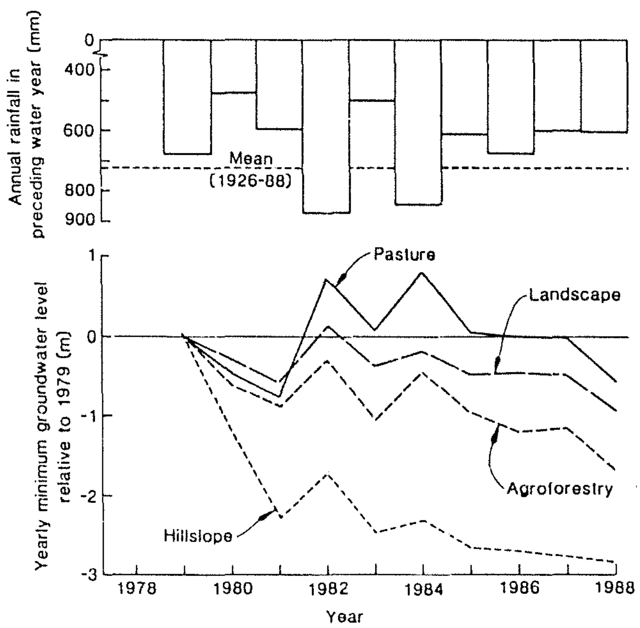


Figure 35 Annual rainfall and groundwater level variations at Flynn's Farm experimental reforestation sites (after Steering Committee, 1989)

At Boundain (500 mm yr^{-1} average rainfall) an agroforestry trial was established in 1981 adjacent to an expanding salt seep. Groundwater occurred at a depth of 1.3 m and had a salinity of 2,000-17,000 mg L^{-1} TSS. Trees were planted at 166 stems ha^{-1} and 83 stems ha^{-1} in 40 x 150 metre plots, with every third plot left with annual pasture. This layout was replicated five times. Tree species were planted according to salinity hazard. Eucalyptus globulus was planted on non-saline areas, E. camaldulensis adjacent to the seep and E. occidentalis , E. sargentii and Casuarina glauca (salt sheoak) on salt-affected land. Over the period 1981-1988 the average groundwater level was depressed beneath reforestation by 1.0 m while groundwater beneath pasture was only depressed 0.25 m (Fig. 36a). The magnitude of the groundwater depression was significantly greater beneath the higher density plantings (166 stems ha^{-1}) than the lower density plantings (83 stems ha^{-1}) (Fig. 36b).

(C) Strip and Block Planting

This strategy involves strategically planting strips or blocks of trees on cleared land, allowing agriculture to be continued on the unplanted areas. Three reforestation trials of this type have been conducted : Flynn's Landscape, Stene's Strip and Bannister.

At Flynn's Landscape site (Fig. 34), blocks of trees were planted on the lower slopes in 1977 covering 8% of the cleared area. Blocks were 50 or 100 metres wide and included E. wandoo , E. camaldulensis, P. pinaster and P. radiata. The initial groundwater depth and salinity beneath the plantations were 2.1 m and 4,600 mg L^{-1} TSS respectively. Over the period 1979-88 there was a depression of groundwater level beneath reforestation of 0.9 m, while beneath pasture there was a reduction of 0.5 m (Fig. 35).

On the Stene's Strip site (Fig. 31), widely distributed strips covering 14% of the cleared land were planted from 1976 to 1978. The strips were 30-40 metres wide and their configuration ensured

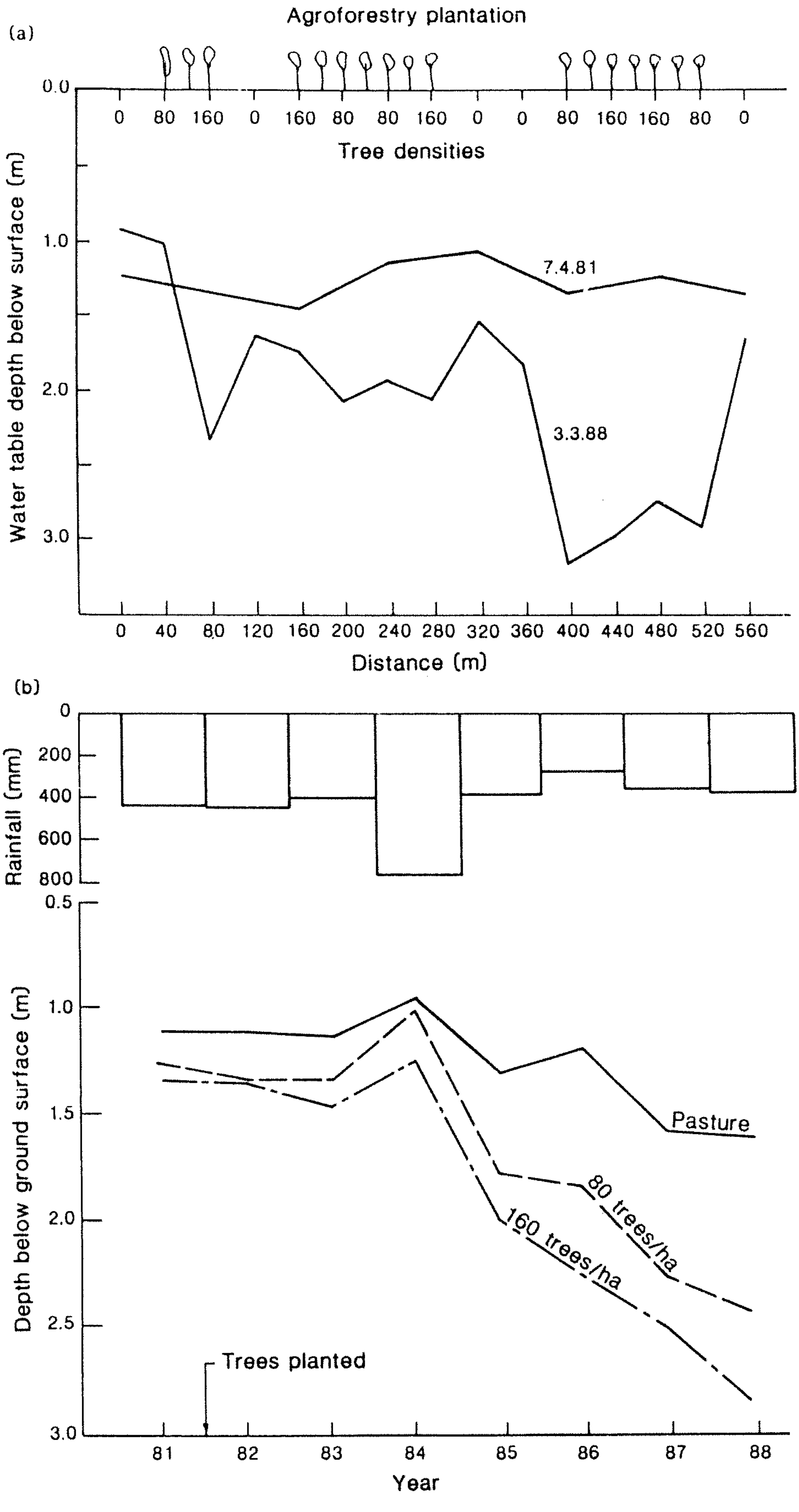


Figure 36 Groundwater and rainfall variations at Boundain : (a) comparison of groundwater levels across the site between 1981 and 1988, (b) annual rainfall and groundwater level variations beneath pasture and agroforestry (after Steering Committee, 1989)

a minimum spacing of 200 m. The main species planted were E. globulus, E. camaldulensis, P. radiata, P. pinaster and E. wandoo. The initial average depth and salinity of groundwater beneath the plantations were 2.7 m and 7700 mg L^{-1} TSS respectively. Over the period 1979-88, the groundwater levels under the strips lowered on average by 0.5 m, whilst under pasture the groundwater level rose by 0.4 m (Fig. 32).

The Bannister site (Fig. 30) was established in 1975 and comprised two block plantings, one upslope and one midslope just above a salt seep. The total area planted covered 14% of the cleared land and included 25 different species. The initial depth to groundwater beneath the plantations ranged from 2-8 m and the groundwater salinity (in 1985) ranged from 1000-9600 mg L^{-1} TSS. Over the period 1977-87 there was no significant lowering of the groundwater table under the plantations and no significant difference to groundwater level under pasture. Measurement of soil water profiles at this site indicated that trees were extracting unsaturated soil water over summer up to depths of 10 m, while water extraction by pasture was limited to a depth of 0.5 m.

The poor performance of the block and strip plantings is attributed to the low proportions of cleared area replanted.

(D) Dense, Extensive Plantations

Dense plantations covering a large proportion of the cleared area have been studied at three sites, Flynn's Hillslope, Stene's Arboretum and Padbury Road catchment.

Flynn's Hillslope (Fig. 34) was planted with E. camaldulensis and E. wandoo at a density of 1250 stems ha^{-1} in 1978 and 1979. The plantation covered 54% of the hillslope which was totally cleared prior to reforestation. The initial depth and salinity of groundwater beneath the plantation were 3.3 m and 7400 mg L^{-1} TSS respectively. The groundwater table was lowered 2.8 m over the period 1979-88 while the groundwater level beneath pasture decreased by 0.5 m over the same period (Fig. 35).

At Stene's Arboretum (Fig. 31) 65 species were planted in 1979 on 0.5 hectare plots covering 70% of the cleared area. The initial depth to groundwater ranged from 1.2 to 19.4 m and the average initial groundwater salinity was 5400 mg L^{-1} TSS. Over the period 1979-1988 there was a net lowering of groundwater level under reforestation by 5.6 m, while under pasture at a nearby site groundwater levels increased by 0.4 m (Fig. 32).

5.3.2 Effect of reforestation area and density on groundwater level

The effectiveness of the various reforestation strategies in reducing groundwater level beneath plantations of age 10 years has been found to depend primarily on the area and density of trees planted. A regression of average rate of water table reduction against proportion of cleared area reforested is shown in Fig. 37a. The four sites included in the regression have similar crown covers (39-47%) whereas the two sites excluded have significantly less crown cover (Flynn's Hillslope 29%, Flynn's Agroforestry 14%). Over the measurement period the groundwater levels beneath pasture at Flynn's and Stene's sites lowered on average by 6 mm yr^{-1}. Using this information and the regression in Fig. 37a, it can be shown that reforestation of 24% of the cleared area is required to lower the water table at a rate of 200 mm yr^{-1} (i.e. 2 m over 10 years) relative to the ground surface.

Rainfall over the measurement period was 10% less than the long term (1926-88) average. If rainfall had been the long term average it is estimated that groundwater levels beneath pasture on Flynn's and Stene's site would, on average, have risen at a rate of 350 mm yr^{-1}. In this case the regression of Fig. 37a indicates that about 57% of the cleared area would need to be reforested to lower the water table at 200 mm yr^{-1} relative to the ground surface.

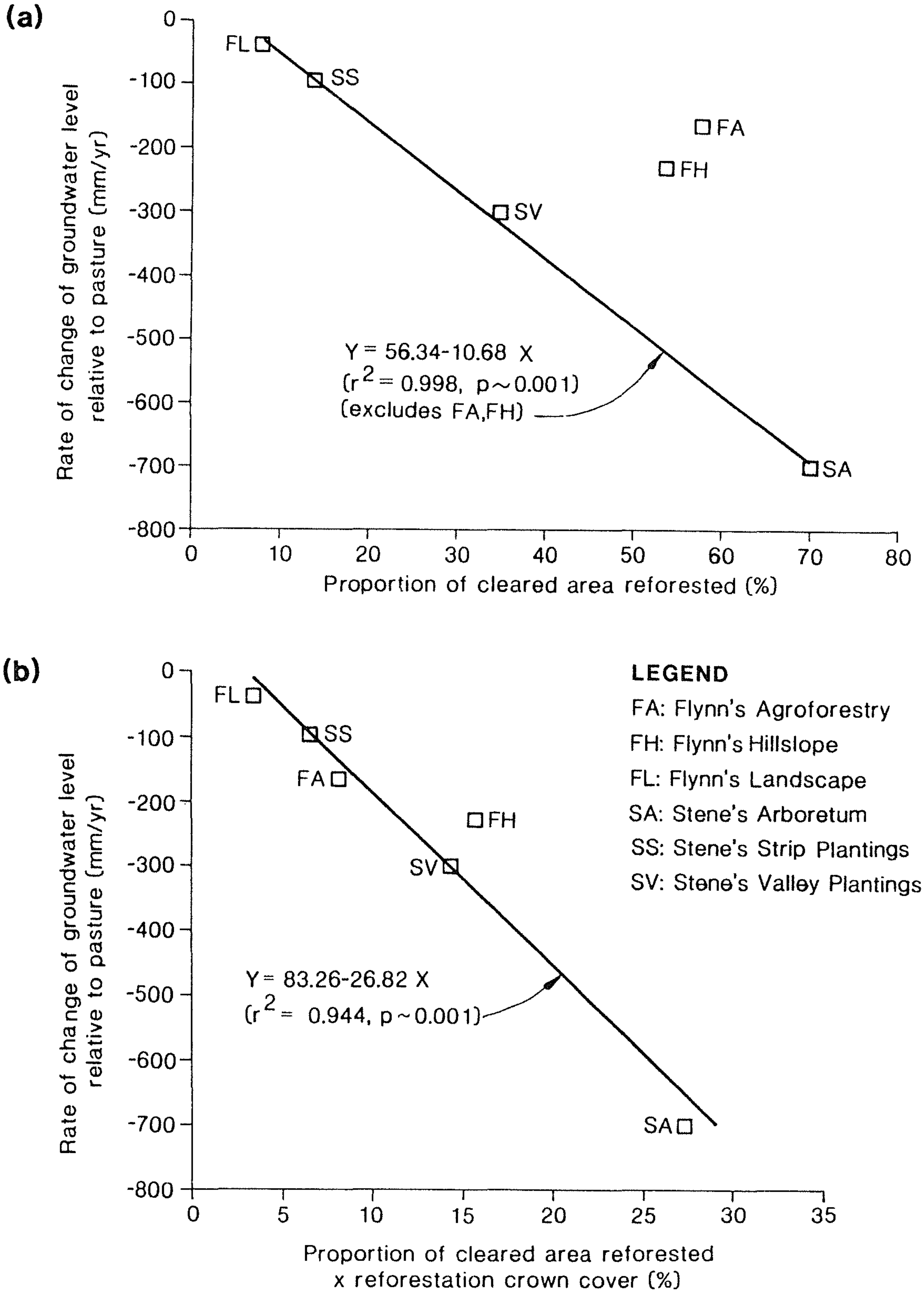


Figure 37 Dependence of mean rate of change of minimum groundwater level under reforestation relative to pasture on (a) proportion of cleared landscape reforested and (b) product of the proportion of the cleared landscape replanted and mean crown cover of reforestation (after Steering Committee, 1989)

A second regression which takes into account the crown cover of the reforestation is shown in Fig. 37b. In this example the average rate of water table reduction was regressed against the 'total percentage tree cover' as represented by the product of proportion of cleared land reforested and reforestation crown cover. The quality of this regression, which includes all sites, implies that total percentage tree cover is the most important factor (for the given reforestation strategies) in the lowering of the water table beneath reforested areas.

5.3.3 Effect of reforestation on groundwater and soil salinity

In the past concern has been expressed about the potential of salt concentration to increase beneath reforestation stands located in valley floor and lower slope locations and affect their long term viability (Conacher, 1982; Morris and Thomson, 1983; Williamson, 1986). Borehole monitoring at all sites above 700 mm yr^{-1} rainfall showed salinity at the water table to have decreased (Schofield et al., 1989). At Boundain, with rainfall of about 500 mm yr^{-1}, groundwater salinities have increased. There is also evidence trees are particularly susceptible to combined salt-waterlogging stress in south-west Western Australia (van der Moezel et al., 1988) in which case lowering the water table would improve the viability of the stands.

Measurement of soil salt content at Boundain showed that, under reforested areas, salt content decreased over the depth range 0 to 0.75 m, increased over the depth range 0.75 to 2.25 m and remained the same below 2.25 m. Under pasture there was little change in the salt content profile.

5.3.4 Effect of reforestation on salt export

The Padbury Road catchment (880 mm average annual rainfall) (Fig. 30) was planted with P. radiata and E. globulus over the period 1977-83. Measurements were taken of stream yield, stream salt discharge and stream salinity and were analysed by Bell et al. (1987). By 1986 it was found that the stream yield and salt discharge of the catchment had decreased in the same proportion, to about 10% of what it would have been without reforestation. Since yield and salt discharge decreased in the same proportion, stream salinity remained almost unchanged. The lack of a decrease in stream salinity may be partly attributed to a small incised area (approximately 4% of the catchment) adjacent to the main stream being left under pasture, which has allowed some continued saline groundwater discharge. The results suggest that intensive reforestation of the type carried out would not improve the water quality of small, local water supplies in the first 10 years and would in fact strongly decrease the water yield. The result is very significant, however, for salinity control in large water supply catchments, because reforestation of the major salt-exporting lower rainfall areas would significantly reduce the stream salinity of the whole catchment. Establishing plantations in the higher rainfall areas of these catchments should be avoided since this would reduce the quantity of fresh water inflow and increase the overall catchment salinity.

5.4 Commercial Potential of Reforestation

5.4.1 The potential of commercial dense plantations for salinity control and timber production

The reforestation method for salinity control employed in the Wellington Dam catchment attached great importance to the water use capacity of the tree species used. This characteristic was required so that the area and density of tree planting, and the level of disruption to agriculture, might be minimised. Considerable work was done to identify species with superior water use. However the results were not conclusive although species able to extract water against higher negative water potentials were identified. Most of these species were of little commercial value.

The approach of the Wellington reforestation programme, which involves purchase of land and the use of non-commercial trees, is costly and disruptive to farming. This situation could be

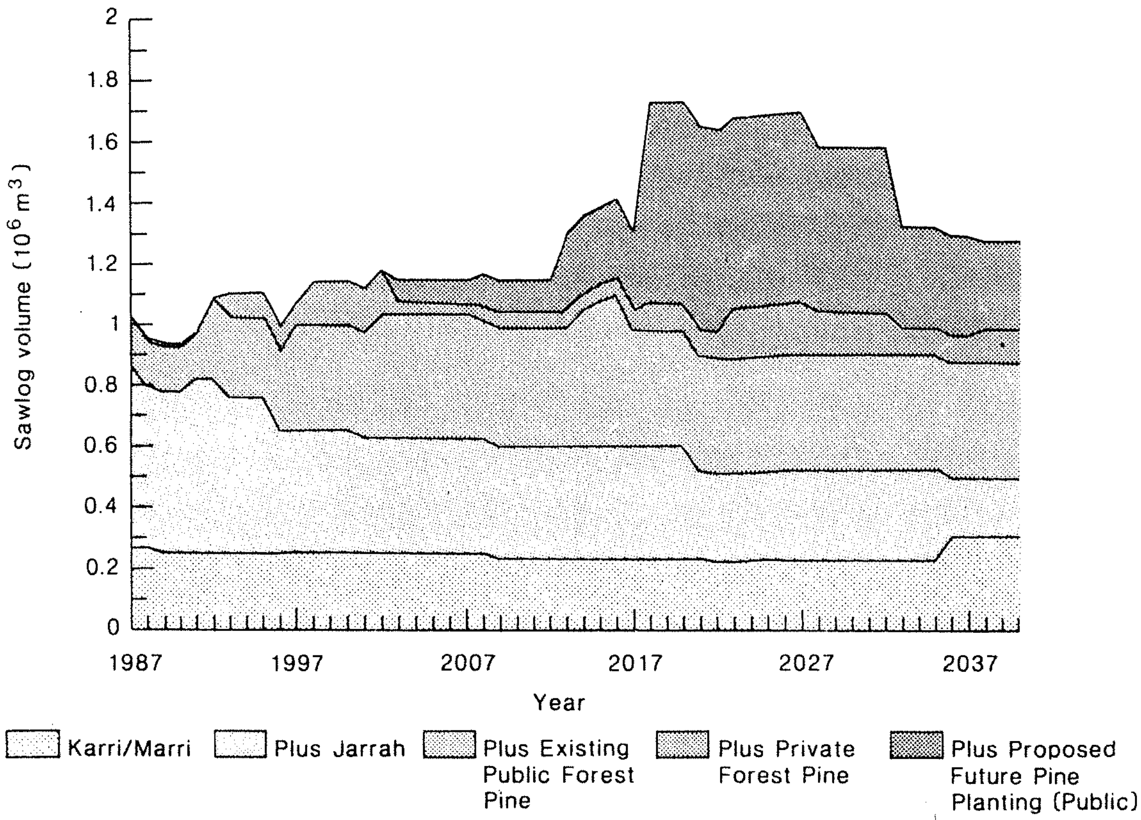


Figure 38 Long term projected supply of sawlogs from public and private forests (after Schofield *et al.*, 1989)

improved by introducing economically attractive tree planting schemes. Fortunately it appears that both the water use and growth performance of potentially commercial species are better than early assessments anticipated. Also, the success of the sharefarming concept has provided a model by which extensive voluntary planting of commercial tree crops by farmers could be undertaken.

A major criterion of commercial suitability should be that the product be saleable on large volume world markets since the prospective area for treatment of land and stream salinity is large (i.e. about 30-50% of the 650 000 ha of cleared farmland in the 600-900 mm rainfall area from south of Perth to just east of Albany). Local or even national markets are likely to be too small to absorb the yield from plantings on this scale; for example the local P. radiata market only requires growth in plantation area of 2000 ha yr^{-1}, far too little to have an impact on salinity at a regional scale.

Pine Plantations

Western Australia has a small local softwood industry. The area of present plantings total 50 000 ha with an annual increase of 2000 ha. The industry has developed to maintain timber supply in the face of a projected decline in the cut from native hardwood forests (Fig. 38). Two main areas and species have been planted:

- Some 23 000 ha of Pinus pinaster have been established on native banksia woodland on the coastal plain north of Perth. Due to modest productivity and conflict with ground water supply no further new plantings are planned, and only the most productive areas will be considered for a second rotation.

- Some 27 000 ha of Pinus radiata has been established in the intermediate and high rainfall zones of the central and southern forest regions with a particular focus in the Blackwood Valley between Bridgetown and Nannup. This is a prime forestry region with long established forestry infrastructure. Plantations have been established predominantly on farmland purchased by the State or corporate investors. Some native forest areas have been converted to pine especially in the Donnybrook Sunkland region between Nannup and Busselton.

Historically there has been little serious consideration of the potential to relocate pine plantation forestry or redesign pine production systems to gain secondary water quality benefits. Relocation into the low rainfall zone has generally been considered to be beyond the productivity limits for pine and to be too distant from established infrastructure. There has also been some uncertainty as to the likely effectiveness of pines in establishing a water balance comparable with native forest in the plateau soil environment (Bartle and Shea, 1978).

However social pressures have forced a re-examination of land selection for pine afforestation. During the 1970s it became apparent that farming communities were opposed to an open-ended expansion of State pine plantation on farmland in some districts. The option of clearing native forest for pine planting also met with increasing resistance from the conservation movement and in 1983 a decision by the State Government closed off this option. Furthermore, the capital cost of land acquisition emerged as another problem in the economic environment of the 1980s. A less obtrusive, less capital demanding means of pine plantation establishment on farmland had to be found.

The independent Centre for Applied Business Research was commissioned to investigate means by which pines could be grown co-operatively with farmers (Treloar, 1984). This study concluded that pine production was economically competitive in comparison to other extensive agricultural crops in the Manjimup area, but that the distribution of costs and returns over time excluded it as an option for most farmers to undertake independently. The Department of Conservation and Land Management therefore developed the Softwood Sharefarming Scheme

(Grant 1986). Under this scheme the State and the farmer contract to share establishment and management costs. The State underwrites expected future revenue, and, after covering its costs, pays to the farmer the discounted revenue surplus as an annuity and variable share of the final revenue. The scheme was not initially attractive to farmers in the Manjimup area where it was first offered. This was apparently partly due to the small property size and the perceived loss of flexibility given the minimum plantation size constraint of 40 ha.

This impasse forced CALM to look further afield. The Albany region was identified as the most prospective target area. Albany is a major regional centre and an appropriate location for the infrastructure required for a timber industry. Property sizes in the hinterland are much larger than around Manjimup. Though lying in the intermediate and low rainfall zone the more moderate temperatures and longer growing season of its southern coastal climate is much more favourable than the inland low rainfall zone climate further north. A rapid reconnaissance of the performance of <u>P. radiata</u> in various small plantings through out the region indicated satisfactory growth potential, and a much reduced proneness to drought death in comparison to the west coast and inland areas with similar rainfalls (G. Ellis, pers. comm. 1989).

When publicised in the Albany region the Softwood Sharefarming Scheme generated considerable interest which opened the possibility of directing plantings into areas where the greatest water quality benefits might accrue. Thus the potential for a commercially driven treatment for salinity emerged. The need to quantify and demonstrate this potential and to combine it with recent advances in agricultural cropping and drainage methods linked in well with the need to arrest deteriorating surface water resources. This led to the development of the Denmark Integrated Catchment Management Project.

Eucalypt Plantations

There is a large international trade in woodchips, woodpulp and paper. Australia is a net importer at a time when world market projections indicate a strong sellers market (Groome 1987). The potentially commercial eucalypt species showing promise include E. globulus, E. saligna, E. botryoides and E. viminalis. These species, native to tall forests in Victoria, Tasmania and New South Wales, have rapid early growth, and young trees in particular produce high quality fibre for paper manufacture.

There are sufficient scattered plantings to provide an indication of appropriate silvicultural practice and likely yield of E. globulus. Yields likely from good quality farmland range from 15 m^3 ha^{-1} yr^{-1} for 600 mm rainfall to more than 30 m^3 ha^{-1} yr^{-1} at 1100 mm rainfall. Rotation lengths will vary from 7 to 14 years for the first cut and 5 - 10 years for subsequent coppice crops. At a projected sale price of \$20 m^{-3} at the stump, the surplus of discounted revenue over costs can provide annuities under a sharefarming contract ranging from \$80 - 240 ha^{-1} yr^{-1}. These returns appear sufficient to be of interest to farmers.

The outlook for a major short-rotation eucalypt sharefarming industry appears very attractive. The State Government and the local timber industry have undertaken a full-scale feasibility study. The State Government recently announced that a Tree Fund would be established to operate a pulpwood industry on a commercial basis.

Using interim arrangements CALM planted some 2000 ha of E. globulus in 1988 and 5000 ha in 1989.

5.4.2 Timber aspects of wide-spaced plantations

The combination of wide-spaced pine for sawlogs and pasture for grazing (agroforestry) has been extensively researched in Western Australia. The first trials were established in 1973 and methods of management have been developed and levels of timber and agricultural production determined (Anderson and Moore, 1987). Tree arrangement and density, culling and pruning practices and farming amongst pines have been evaluated and firm guidelines provided (Dept. Conservation and Land Management, 1987d). Some more recent developments in this area were mentioned by Moore (1988). An economic study of agroforestry with P. radiata in the Manjimup region (Malajczuk et al., 1984) found that in the long term agroforestry can be substantially more profitable than a grazing enterprise alone. A disadvantage is the long wait for returns from the timber crop. This can be largely offset by planting only a small proportion of a farm at any one time and staggering plantings to spread out the effect of lost grazing. Compared with dense plantation forestry, agroforestry has the advantage that substantial returns from agriculture can be obtained while the trees are growing. This can be a very important benefit, especially for farmers who wish to be independent and finance tree growing themselves. Growing the trees at wide-spacing enables the farmer to continue to obtain an income from agriculture.

Levels of pasture production and livestock carried under various ages and densities of P. radiata agroforestry were determined at Flynn's Farm by Anderson et al. (1988) and are summarised in Table 5. High levels of agricultural production can be maintained in the early years of the plantation but it declines with age. Agricultural production is also sensitive to stand density, declining with higher stand density for a given age.

The wide-spaced method of tree growing also enables tree growing for timber production to be extended to areas with lower rainfall. The eastern parts of most water resources catchments receive too little rain to support extensive dense plantations of trees.

Research into wide-spaced eucalypt plantations has become prominent in recent years. This has come about for a number of reasons: farmers have a strong preference for eucalypts rather than pine; eucalypts can be planted on sites unsuitable for pine;

Table 5: Mean height, mean diameter at breast height over bark (DBHOB) and mean DBHOB increment of eucalypts at a density of 150 trees per hectare

	Height (m) (age 5.5 yrs)	DBHOB (cm) (age 6.5 yrs)	DBHOB increment (cm/yr) (age 5.5 to 6.5 yrs)
E. globulus	11.85	24.45	5.10
E. paniculata	7.55	14.30	2.65
E. muellerana	8.20	18.05	3.65
E. maculata	10.30	18.45	3.50
E. oreades	8.90	17.45	4.05
E. diversicolor	10.70	20.25	4.30

Table 6: Pasture produced and livestock carried under various ages and densities of *P. radiata* agroforestry as a percentage of open pasture (after Anderson *et al.*, 1988)

Age (yrs)	Stand density (trees/ha)	Pasture produced (%)	Livestock carried (%)
6–7 *	0	100	100
	100	87	82
	300	76	73
20 **	0	100	100
	70	67	59
	150	39	24

Notes: * pruned to 4 m, ** pruned to 6 m the need to satisfy future demand for high quality hardwood sawlogs; and the potential of the eucalypt pulpwood industry.

The objectives of management of wide-spaced eucalypt plantations are to produce high quality sawlogs in conjunction with pasture for grazing or cropping. Trials began in the late 1970s. Several eucalypts have exhibited fast growth rates and suitable form. Some growth data from a trial near Busselton are presented in Table 6 (Moore, 1988). It has also been found that the natural tendency of eucalypts to self-prune greatly reduces the cost of pruning compared with pine.

5.5 Wellington Dam Catchment Project

Wellington Reservoir has the largest water yield of any individual reservoir in the south-west of Western Australia (approximately 100 x 10^6 m^3). The continued increase in its inflow salinity has necessitated an active programme of catchment management and rehabilitation. The catchment spans a rainfall range from over 1200 mm yr^{-1} in the west to 600 mm yr^{-1} in the east of the catchment (Fig. 39). Clearing of some of the original jarrah forest for agricultural development has resulted in major increases in stream salinity. This section summarises the history of stream salinity increases, and the catchment management measures introduced to minimise these increases.

5.5.1 Early clearing history and subsequent increases in stream salinity

Prior to agricultural development the salinity of the Collie River at Wellington Dam has been estimated to be between 200 and 250 mg L^{-1}. Agricultural development commenced at the turn of the century and expanded slowly over the following 30 years. No salinity problem was evident when the small irrigation dam was constructed in 1933. Growth in agricultural development virtually ceased through the depression years and it was not until the 1950s that agricultural development again expanded. To service increased demand for both irrigation on the coastal plain, and water supply in the wheatbelt towns of the Great Southern District, Wellington Dam was raised to its current height during the late 1950s. By this time serious salinity deterioration was apparent on small streams in the headwaters of the catchment and in 1961 the State Government, through administrative action, prevented further alienation of Crown land in the catchment.

In the late 1950s land clearing accelerated and extended upslope from the valleys where most of the early clearing had occurred. This was reflected in increased salinity through the late 1960s and early 1970s. By 1972/73 average inflow salinity was about 540 mg L^{-1} and was increasing at 22 mg L^{-1} per year. In the dry year of 1972/73 the inflow salinity was 685 mg L^{-1}. The trend in the inflow salinity (adjusted to a median inflow year) over the last 40 years is shown in Fig. 40.

5.5.2 Clearing controls and the effects of past clearing

Realising the seriousness of the then current salinity levels and recognising that the full effect of past clearing was not yet reflected in the inflow salinity at that time, the State Government introduced legislation to control further clearing for agriculture in November 1976. The Country Areas Water Supply Act was amended to prohibit unlicenced clearing on the catchment. While small scale, essential clearing is licenced, large scale agricultural development is not permitted. Farmers affected can claim compensation for their inability to further develop their farm enterprise. Application of the legislation has effectively held the level of clearing to 64 000 ha or 23% of the total catchment and has avoided the expansion of agriculture to a possible 100 000 ha or 35% of the total catchment.

A means of predicting the effects of clearing on inflow salinity was developed by the mid-1970s. Prediction at the time indicated that if the level of clearing was maintained at the 1976 level

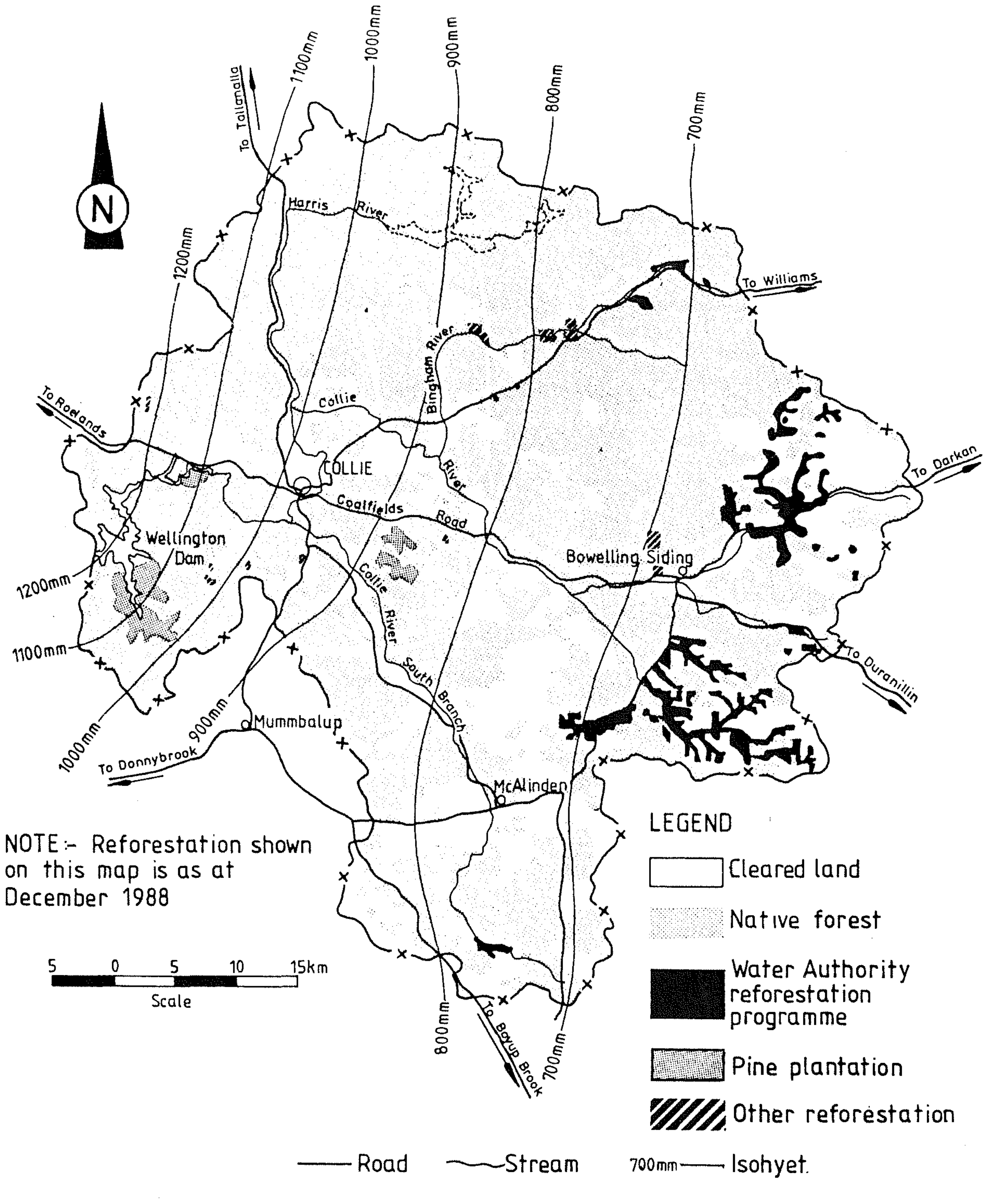


Figure 39 The Wellington Dam catchment, showing areas of cleared land and reforestation (after Steering Committee, 1989)

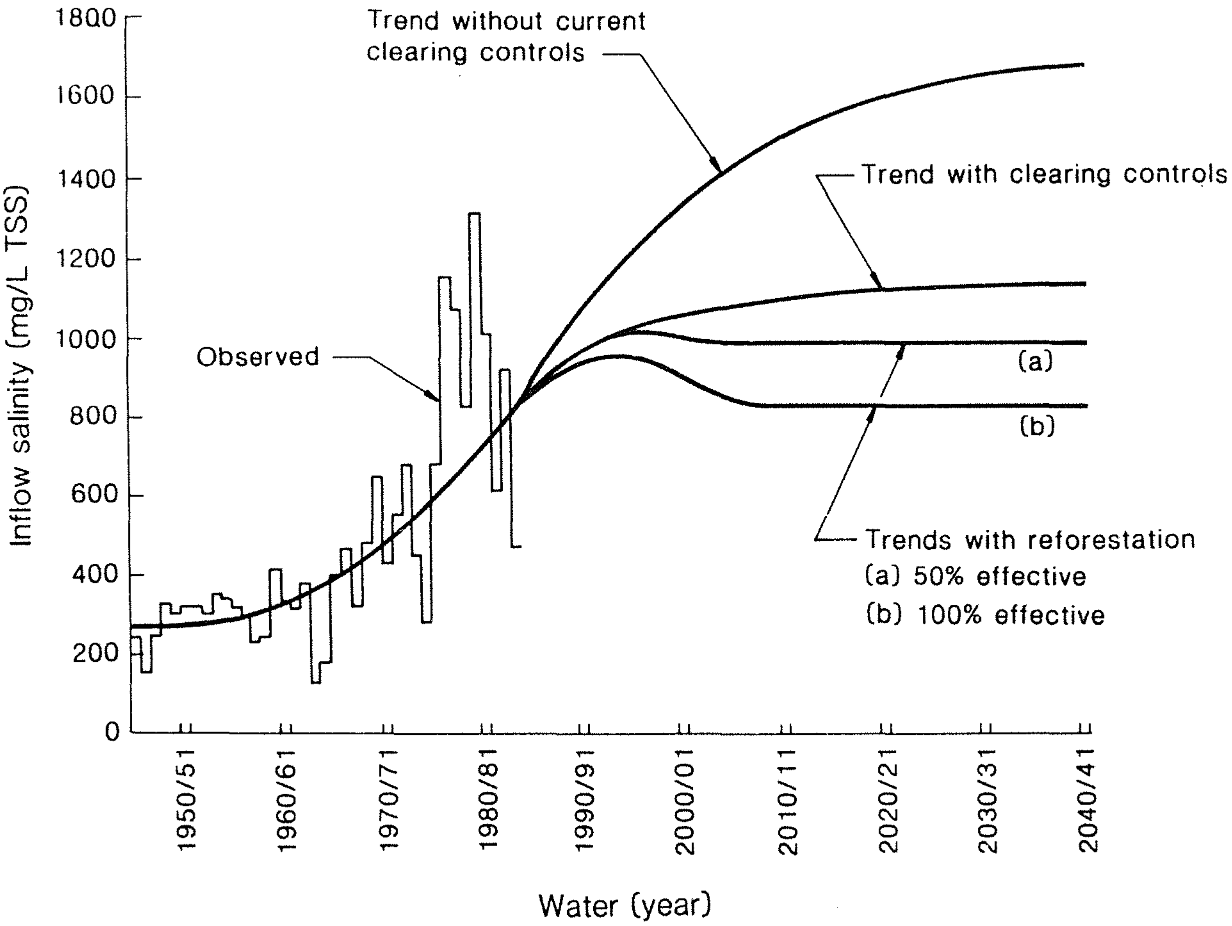


Figure 40 Observed and predicted inflow salinities to Wellington Dam for various salinity control measures (after Schofield et al., 1989)

the salinity of inflow in a median year would reach a maximum of about 1100 mg L^{-1} TSS. Subsequent detailed groundwater simulation studies support the original estimates. The groundwater simulations indicate that the salinity in a median inflow year would reach a maximum of 1150 mg L^{-1} TSS in 2040, in the absence of reforestation (Fig. 40). In a dry year (10 percentile inflow) the inflow salinity could reach 1900 mg L^{-1} TSS by 2040.

5.5.3 The reforestation programme and predicted salinity improvements

While the clearing control legislation has had a major effect in minimising further deterioration in reservoir salinity levels, estimates of the full effect of clearing current at the time of the legislation indicated the quality of both town water and irrigation supplies would eventually become unacceptable, particularly in dry years. In addition the deterioration would limit the future utility of the presently uncommitted yield from Wellington Reservoir. Following consideration of a number of options, reforestation of cleared farmland in the drier, high salt-yielding parts of the catchment was commenced in 1979/80.

The reforestation programme was initially proposed to run for six to ten years with an annual replanting target of 2000 ha. The actual planting rate achieved has varied between 700 and 800 ha per year, with a total of 5737 ha having been reforested to the end of 1988. The areas planted have been concentrated in the eastern and southern portion of the catchment where the annual rainfall is usually less than 750 mm per annum (Fig. 39). The reforestation strategy involved planting along the valley floors and lower sideslopes, the remaining middle and upper slopes providing viable strips of cleared farmland which could then be exchanged for lower slope areas on adjacent farmland to further extend the area of reforestation.

In 1985 the reforestation programme was viewed as part of the environmental assessment for the Harris Dam Project and a target planting area of 8000 ha was established. This programme should exert control over salt discharge from 18 500 hectares of the 51 000 ha of cleared farmland in the high salt-susceptible zones of the catchment. At the current rate of 700 to 800 ha yr^{-1} the programme should achieve 8000 ha by the early 1990s.

With the current planting rate and present knowledge of groundwater responses to reforestation, inflow salinities to Wellington Reservoir are not expected to reduce until the middle to late 1990s. Fig. 40 shows the estimated effect of the current reforestation programme on inflow salinities in a year of median inflow. Two levels of control over saline discharge have been assumed. If the programme is moderately effective (reducing groundwater discharge by 50%) the average inflow salinities are likely to peak in the mid-1990s and return to about 1000 mg L^{-1} by the year 2010. This is similar to the current estimated average inflow salinity. If the reforestation is 100% effective and reduces groundwater discharge to zero, then it is predicted that salinities could be returned to 850 mg L^{-1} TSS by 2010. Much higher salinities will of course occur in drought years.

6. SILVICULTURE TO INCREASE WATER YIELD

6.1 Introduction

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

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

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

6.2 History of Forest Logging

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

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

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

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

6.3 Silviculture for Wood Production

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

Three basic stand treatments were proposed:

(i) Thinning: a stand is amenable to thinning when sufficient crop trees are available for retention. Typically, regrowth stands have a tree basal area greater than

30 m^2 ha^{-1}. Fig. 41 shows the relationship between stand growth rate and stand basal area. Maximum stand growth occurs in the basal area range 10-25 m^2 ha^{-1}. By thinning down to 10 m^2 ha^{-1}, the total growth rate of the stand is maintained while the growth rate of individual crop trees is more than doubled. Depending on average tree size and marketability, a basal area of 10-15 m^2 ha^{-1} is normally retained in thinning. Where slightly less than 10 m^2 ha^{-1} of suitable jarrah crop trees are available, the thinning treatment may still be applied but some marri and sheoak may be retained. However, these commercially less attractive species are not retained within four metres of a jarrah crop tree, the objective being to release the crop tree from immediately adjacent competition. This form of thinning is known as individual tree release.

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

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

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

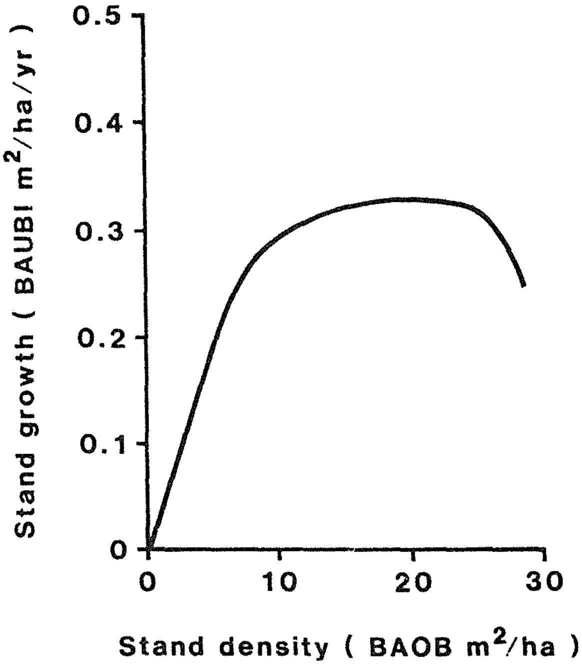


Figure 41 The stand density (BAOB - basal area over bark) - stand growth (BAUBI : basal area under bark increment) relationship for a regrowth jarrah pole stand (after Steering Committee, 1989)

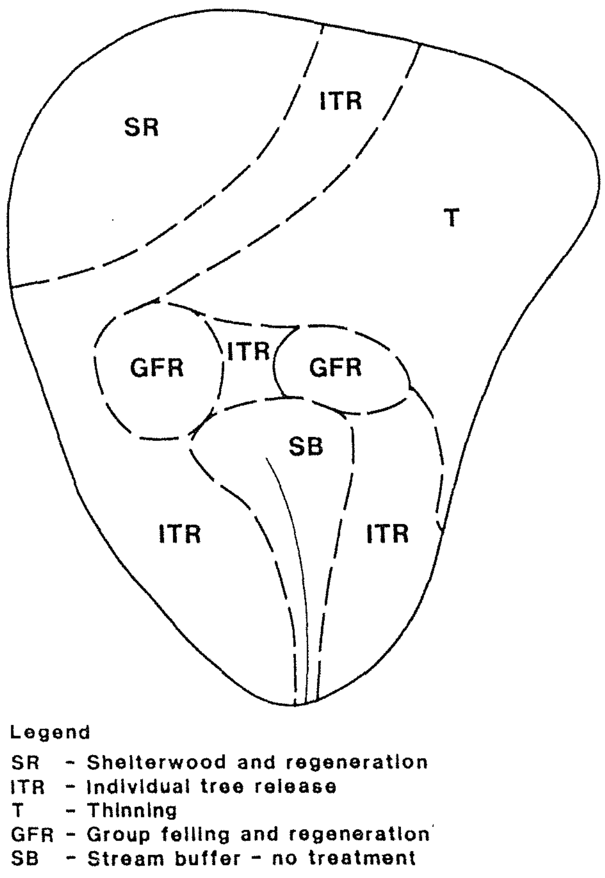


Figure 42 Schematic of silvicultural treatments applied to a catchment for water production (after Steering Committee, 1989)

6.4 Silviculture for Water Production

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

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

(b) The target basal area desirable for wood production alone is in the range 10-15 m^2 ha^{-1}. For both wood and water production, a lower range might be appropriate, even though this would involve some loss of wood production potential.

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

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

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

In silviculture for water production, a range of treatments would be implemented in any one catchment. This situation is depicted in a simple schematic form in Fig. 42. In practice the situation may be more complex since factors such as dieback occurrence and hazard must be considered in the allocation of treatments.

6.5 Areas Available for Silvicultural Treatment

A preliminary survey of areas suitable for silvicultural treatment in the current water supply catchments has been completed. In the high rainfall zone (annual rainfall greater than 1100 mm yr^{-1}), it is estimated that about 460 km^2 are available, and it is estimated that about 540 km^2 are potentially suitable in the intermediate rainfall zone (annual rainfall between 900 mm and 1100 mm). These estimates have been derived from broad-scale forest information and probably represent a slight over-estimation. A detailed inventory of forest attributes is necessary to refine these figures.

6.6 Evidence for Streamflow Increases following Forest Reduction in Western Australia

Catchment studies of the effects of thinning on streamflow are in the early stages. An evaluation of potential streamflow increases was carried out by Stoneman and Schofield (1989) using four different approaches. Two of these approaches are briefly mentioned here.

The first approach was to examine streamflow increases following forest reduction other than thinning. These includes such activities as agricultural clearing (total clearing, strip clearing, parkland clearing, etc.), clearfelling and regeneration and selection logging and regeneration. These treatments have been applied to research catchments in south-west Western Australia. The resulting streamflow changes are shown in Table 7. High streamflow increases occurred under conditions of large forest reduction, high rainfall and permanent groundwater discharge at the ground surface. Where forest regeneration occurred, streamflow increased following clearing or logging but later (after 4 years) began to decline.

The second approach was to examine the relationship between streamflow and canopy cover. This relationship is shown for high rainfall (>1100 mm yr^{-1}) and intermediate rainfall (900-1100 mm yr^{-1}) areas of the northern jarrah forest in Figs. 43 and 44. The regressions were used to estimate streamflow increases for a specified reduction in canopy cover.

The regression for the high rainfall zone (Fig. 43) predicts a streamflow increase of 237 mm or 18.2% of rainfall by reducing canopy cover from 50 to 20%. The regression for the intermediate rainfall zone (Fig. 44) predicts a streamflow increase of 115 mm (11.5% of 1000 mm rainfall) by reducing canopy cover from 50 to 20%. The canopy-cover differences between catchments are mainly

TABLE 7 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	PCF100-46	1976-83	17	2.1	279	38	4.8	No
Dons	800	Agricultural block, strip & parkland clearing	PCF100-62	1976-83	11	1.4	286	38	4.8	No
March Rd	1070	Clearfelling & regeneration	CC65-0	1982-85	121	11.3	147	196	18.3	Yes
April Rd North	1070	Clearfelling leaving 100 m buffers	CC65-0 buffer 10%	1982-85	104	9.7	167	155	14.5	Yes
Lewin South	1220	Selection cut & regeneration	CC70-11 BA44-7	1982-85	116	9.5	81	178	14.6	Yes
Yerraminnup South	850	Logging leaving 50 m buffer & regeneration	CC70-10 buffer 12% of area BA44-5	1982-85	20	2.3	83	38	4.5	No
Wellbucket	700	Selection cut & regeneration	CC38-20	1977-81	2	0.3	128	3	0.4	No

cc = crown cover (%), BA = basal area (m^2 ha^{-1}), PCF = % of catchment forested

due to dieback (especially for high-rainfall-zone catchments). Dieback occurs preferentially in valley floors and is also associated with areas of higher lateral soil water flow (Shea et al., 1983). This may cause some bias in the estimation of streamflow increase using the regressions of Figs. 43 and 44.

6.7 Estimated Increases in Stream and Reservoir Yield from Existing Water Supply Catchments

Estimated streamflow increases in water supply catchments

Individual catchment streamflow increases were estimated by multiplying the area of the catchment suitable for silviculture for water production by the lowest estimate of streamflow increase for each rainfall zone (Table 8). The estimated catchment streamflow increases range from 25% to 81% of long-term mean annual flows. The estimated total streamflow increase amounts to 127 million cubic metres or 47% of the long-term mean annual flow. This amount is approximately equally divided between the high rainfall zone and the intermediate rainfall zone.

Estimated reservoir yield increases from water supply catchments

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

The potential increase in reservoir yield has been determined by running the Metropolitan Water Supply System computer simulation model with the projected increased streamflows (G. Mauger pers. comm.). A variety of options have been simulated and are summarised in Table 9. With the current limitations on combined trunk main capacity, the potential yield increase of the water supply system resulting from a full thinning programme in the high and intermediate rainfall zones is 37% of the estimated streamflow increase. This proportion could be increased to 53% if the trunk main capacities were upgraded. If only the high rainfall portion of the area available for thinning was treated, then 57% of the estimated streamflow increase would be utilized. Moreover, with the current trunk main capacity, this represents 77% of the increased yield from both and intermediate rainfall zones.

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

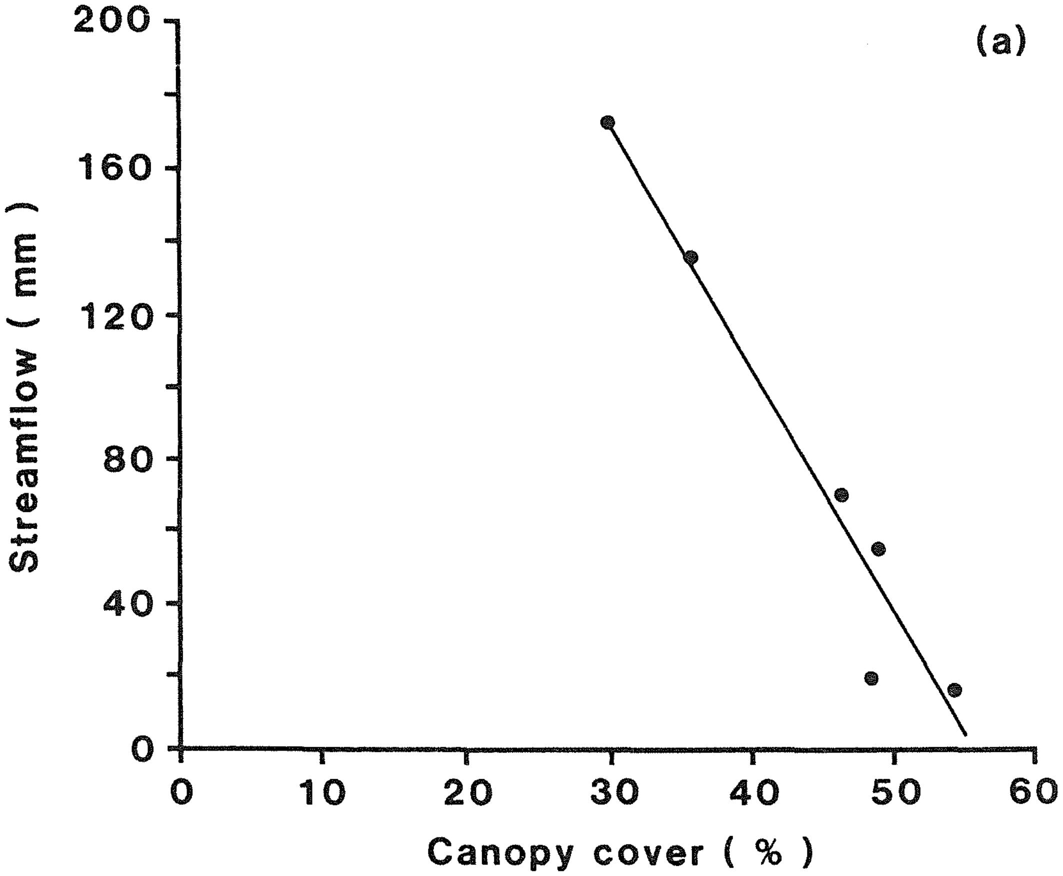


Figure 43 Relationship between canopy cover (%) and streamflow (mm) for six catchments in the high rainfall zone of the northern jarrah forest ($y = 371 - 6.678x$, $r^2=0.94$) (after Stoneman & Schofield, 1989)

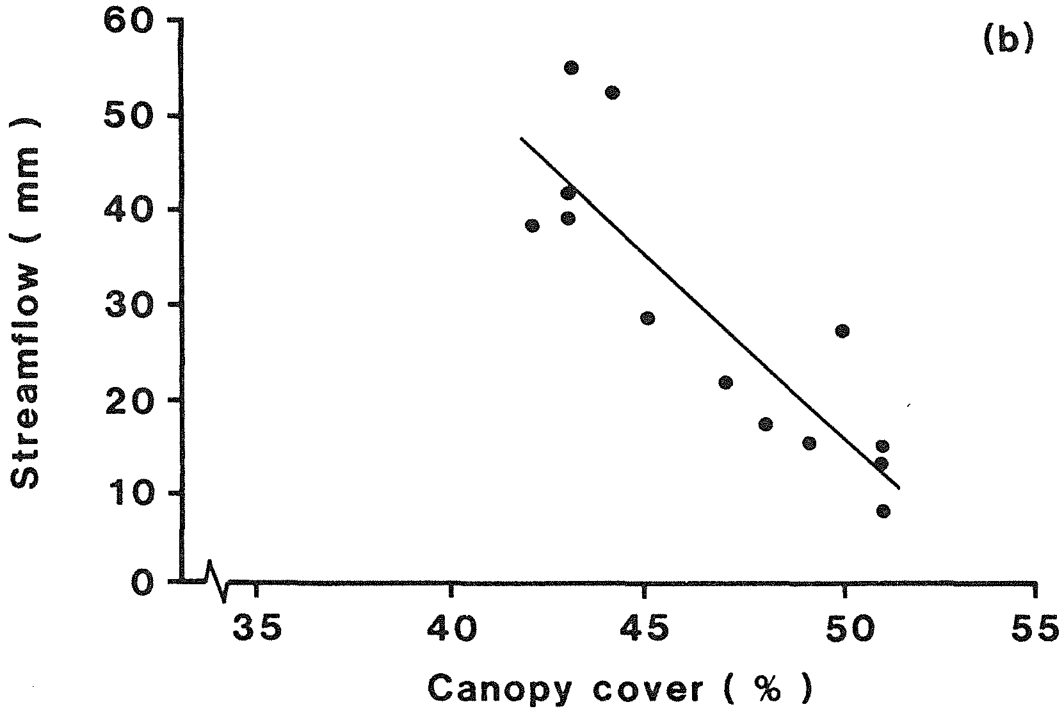


Figure 44 Relationship between canopy cover (%) and streamflow (mm) for 13 subcatchments of the Yarragil catchment in the intermediate rainfall zone of the northern jarrah forest ($y=208 - 3.83x$, $r^2=0.75$) (after Stoneman and Schofield, 1989)

Table 8 Estimated streamflow increases for individual water supply catchments

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

HRZ : high rainfall zone

IRZ : intermediate rainfall zone

Thinning of the South Dandalup catchment alone has been included in Table 9 because this catchment is considered suitable for a large-scale trial thinning project. With the current trunk main capacity, some 13.6 million cubic metres or 53% of the estimated streamflow increase is potentially available.

Estimated costs of water production by silviculture

The total forest area in the high and intermediate rainfall zones suitable for silviculture for water production is estimated at 1010 square kilometres. The cost of silvicultural treatment has been estimated to range from \$1100 to \$3700 per square kilometre averaged over 15 years (depending on the type of treatment carried out). On this basis, the cost of adding the estimated 48 million cubic metres to the Metropolitan Water Supply would range

Table 9 Simulated increases of the Water Supply System* for a range of options

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

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

from 2.3 to 7.9 cents per cubic metre. If only the high rainfall zone was treated, the cost of producing the estimated yield increase of 37 million cubic metres would range from 1.4-4.7 cents per cubic metre. Both of these costs compare favourably with the development of a new dam, the cheapest of which would provide water at 20 cents per cubic metre (Mauger, 1987).

6.8 Implications and Uncertainties

Interaction with jarrah dieback

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

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

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

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

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

Stream salinity

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

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

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

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

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

Areas suitable for water production

Detailed Forest Inventory

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

(i) potentially treatable area;

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

(iii) topographic distribution of areas and types;

(iv) rainfall and catchment.

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

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

Interaction with bauxite mining

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

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

Ecological impacts

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

Reliable estimates of streamflow increases

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

Implications for streamflow distribution, floodplain management and spillway design

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

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

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

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

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APPENDIX I "REHAB. 89"

PRESCRIPTION FOR REHABILITATION OF BAUXITE MINES IN THE WESTERN JARRAH FOREST

1. INTRODUCTION

1.1 Environmental aspects of bauxite mine planning, operations and rehabilitation in the jarrah forest are complex. Overlapping tenures and legislation are involved, together with interactions between land use and biological factors.

1.2 However, the complexity of the system must not deter the formulation and clear statement of objectives, strategies and most up-to-date techniques. This statement can then provide an agreed basis for review and up-date by all parties involved as well as operating guidelines for field personnel.

1.3 The first such statement was entitled "Rehab. 80". It was produced by the Department of Conservation and Land Management (C.A.L.M.) in consultation with Alcoa.

1.4 Following a period of implementation and further research and analysis by Alcoa and C.A.L.M., previous prescriptions were withdrawn and replaced by this prescription after joint review.

Rehab. 89 is the current document describing techniques to be used in bauxite mine rehabilitation in the higher rainfall zone of the jarrah forest.

1.5 New techniques (i.e., departures from this prescription) may be introduced as research projects, as long as:

- the location and timing is approved by C.A.L.M. in consultation with the Water Authority where water catchments are concerned.
- accepted research procedures for experimental design, measurement and follow-up are fulfilled.

1.6 The prescription will be reviewed annually, at which time new strategies or techniques will be considered for incorporation.

Input for this review will be considered from the interested groups or those involved in the rehabilitation operation. The review will be co-ordinated by C.A.L.M. Any proposed changes to objectives, strategies or operational techniques will be fully documented, outlining the reasons, and detailing the data to support the proposed change. They will be subject to comment and acceptance by appropriate government authorities and the mining company.

2. THE OBJECTIVE

Bauxite mine rehabilitation is to be consistent with the Regional Management Plan. The overall objective of bauxite mine rehabilitation in the jarrah forest is to maximise the forest's potential by:

Establishing a stable, self regenerating forest ecosystem, planned to enhance or maintain water, timber, recreation, conservation and/or other nominated forest values.

Specific goals (not listed in order of importance since priorities may vary with designated land use) are:

2.1 Water values: to ensure that mined areas provide acceptable water quality and quantity.

2.2 Timber: to grow a forest which has the potential for sawlog production.

2.3 Recreation: to maintain existing recreational values where possible and to provide increased opportunities for forest based recreational activities in accordance with C.A.L.M. regional and district recreation plans.

2.4 Protection: to conserve the residual soils; to control dieback spread and to manage potential fire hazards.

2.5 Landscape: to create a rehabilitated landscape visually compatible with the adjoining indigenous forest.

2.6 Conservation: to encourage the development of floral, faunal and soil characteristics of the indigenous jarrah forest ecosystem.

2.7 Economical management: to produce a rehabilitation system which can flourish (in the short term) and become self sustaining (in the long term) without continual applications of nutrient/management resources.

To meet multiple use forestry goals, long term rehabilitation management must be compatible with that of surrounding jarrah forest (in terms of points 2.1 - 2.7).

3. REHABILITATION STRATEGIES

These are:

3.1 The development of prescriptions for rehabilitation procedures for each mined area, in accordance with the designated land use priority and land use management plans.

3.2 To conduct research programmes to improve rehabilitation procedures. In the event of research information becoming available, then modification to this prescription may take place before the next review by mutual agreement.

3.3 The monitoring of rehabilitated areas to determine their capacity to sustain long-term production of the forest values listed in the objective, and

3.4 The development of remedial treatments should monitoring reveal that rehabilitation objectives are not achieved.

4. REHABILITATION PLANNING

Rehabilitation planning occurs at two levels:

i) The first is broad-scale regional mine site planning on a five year time scale.

ii) The second is annual detailed operational planning on a pit-by-pit basis.

4.1 Regional Planning: the mining company is required to produce an annually updated five year mining and management plan for government approval. Those plans should be drawn up in consultation with appropriate government departments and should consider the following regional aspects:-

- the sequence of mining and rehabilitation
- access for mining, public and future management
- location of mine facilities
- dieback management
- aesthetic and landscaping considerations
- fire protection planning
- integration of mining into land use plans so as to minimise adverse impact on priority uses
- requirements for long-term management
- broad description of site vegetation types and reconnaissance for rare flora and fauna
- water management systems and water course protection
- proximity to private property.

4.2 Annual Operational Planning : detailed conceptual proposals for each mine pit should be prepared before rehabilitation. Each proposal should be jointly prepared by C.A.L.M., mining company staff and the Water Authority in water catchment areas and should consider the following specific factors:-

- pit identity
- dieback management, drainage, erosion control and water management, specifying measures to be used from initial drilling through to completed rehabilitation;
- treatment and management of land over non-ore bodies within and adjacent to ore i.e. "islands" of unmined forest;
- species to be used;
- any special features to be incorporated or retained (e.g. pit walls) as part of the rehabilitated landscape;

- internal access to pits for future forest management;
- location of mining facilities/structures;
- scheduling in sensitive areas;
- rock management;
- movement, stockpiling and replacement of top soil and overburden, in relation to dieback spread within and downslope of the pit.
- identification of features such as permeability, slope, waste islands, rocks, state of forest downslope, wetness of pit, thin overburden, sudden slope changes etc, which may require special handling;
- any research projects on the pit, including method and timing of decommissioning of the project at its conclusion.
- The long term management strategy for the rehabilitated area as planned by C.A.L.M.

The conceptual rehabilitation plans will be endorsed by the C.A.L.M. District Manager following discussions with other government agencies where appropriate.

Contentious or unusual areas will be referred to the Regional Manager or the Mining Operations Group.

Research proposals frequently will not be finalised until after the completion of conceptual plans. Such proposals, in the form of approved working plans, should be submitted no later than the 1st of December. Where the research project differs significantly from standard practice the means and time of decommissioning the project should be specified.

Research proposals, and other departures from the conceptual plan, should be jointly considered by the C.A.L.M. District Manager and the Company and interested Government departments.

4.3 Fire Protection Provisions

These are outlined in detail in Fire Protection Plans produced for each mine site. When conceptual plans are submitted to C.A.L.M., the District Manager should ensure they comply with the Fire Protection Plan for the relevant mine site.

5. DIEBACK MANAGEMENT

Bauxite mining and rehabilitation involves massive soil and vehicular movement under all weather conditions. Also mining can cause substantial modification to natural drainage patterns in the forest so close attention to dieback management is essential.

The two key management aims are:

i) to minimise the spread of infection into dieback-free forest and mine sites.

ii) to manage access and drainage so as not to expand areas which favour the survival and severity of the disease.

Dieback management practices are specified in detail in other prescriptions dealing with drilling, timber salvage and clearing. i.e., operations not dealt with in this prescription.

Dieback management practices following clearing are to be in accordance with the following:

5.1 Disease boundaries established during clearing are to be maintained and demarcated in the field with pegs. Pegs are to be painted green on one side, yellow on the other. The yellow side of the peg-line will indicate the infected area.

5.2 Stripping operations will segregate infected and uninfected soil. Stripping equipment should not access uninfected areas across unstripped infected areas.

5.3 Infected top soil and overburden should either be stockpiled in situ or transferred only to an immediately adjacent infected rehabilitation site. It should not be transported across uninfected areas.

5.4 Uninfected topsoil and overburden may be transferred to remote locations. Such material should be replaced with due consideration to the quality of native forest downslope of the mining area and the potential for restoration of jarrah within the rehabilitated mine pit.

5.5 Topsoil and overburden handling operations for uninfected material should be scheduled for dry soil conditions.

A categorisation process will be undertaken by C.A.L.M. District Managers and the mine sites within their jurisdiction, which will identify those areas of high quality forest where pre-mining operations should occur under dry soil conditions.

6. PREPARATION OF PITS FOR PLANTING

6.1 When mining is completed, the following earthworks will be carried out.

6.1.1 Deep ripping of compacted pit floors which may be covered with more than 0.5 metres of fill.

6.1.2 Landscaping.

6.1.3 Replacement of overburden, then top soil.

6.1.4 Deep or shallow ripping, or scarification as required. (See 6.6)

6.1.4 The construction of water management structures such as contour and grade banks, waterways and sumps.

6.2 Landscaping: Pit walls will be battered and smoothed. Waste islands, and pit floor will be shaped and filled. Occasionally pit walls may be retained if prescribed in a recreation plan. In this case visitor safety needs to be considered e.g. perched boulders, long-term stability of cliff wall.

6.3 Overburden and top soil will be evenly respread over all areas to be rehabilitated. The distribution of this material from pit to pit will be in accordance with the following requirements:

i) No transfer of infected material to dieback free sites which are above significant areas of dieback free vegetation.

ii) Endeavour to move soil under moisture conditions appropriate to its dieback status in accordance with arrangements agreed with the District Manager.

6.4 Unmined areas

Islands or inliers of low grade ore often occur within a pit. Clearing of these areas should be kept to an absolute minimum. However, there will be occasions when they are both cleared and stripped. When this need occurs, it will be justified to the satisfaction of the District Manager.

When this occurs, either the area will be completely landscaped or the unmined caprock will be 'popped' with explosives to provide planting sites and minimise surface runoff. The exception to this will be those areas, identified on conceptual plans as being within a noise restriction zone or inside safe blasting distance from private property. Blasted craters will be graded level before respreading overburden and top soil. Overburden/top soil should be at least 30 cm. deep and scarified, on contour as an aid to erosion control. Deep ripping in these areas should normally be avoided in order to reduce the appearance of surface rocks.

Vegetation establishment and growth on unmined areas have tended to be less successful than that of the adjacent rehabilitated mine pits.

In addition to the routine planting and/or seeding of these sites a supplementary seeding mix will be applied.

This mix will contain drought tolerant tree and understorey species. Seed of E. drummondii, E. sideroxylon and E. microcarpa will be applied to achieve a stocking rate of 625 trees per hectare. The understorey seed will be spread at 1 kilogram per hectare and contain only species endemic to the Darling Range.

6.5 Rock management

During the pit preparation work, care must be taken not to import, or bring to the surface, large boulders - which would make the future forest floor untrafficable. If boulders are brought to the surface enough rocks must be removed from the rehabilitated area to allow access for future management including fire control, silviculture, and other tending or harvesting operations. The removal of rocks may occur before or after planting provided the objective of avoidance of soil compaction and erosion control are not compromised and plants are not damaged.

6.6 Ripping

Deep ripping is required to fracture the compacted pit floor to allow root penetration and, water infiltration; to provide an "anchor" for the returned top soil; and to control the overland flow of water. Joint inspection by C.A.L.M. and Alcoa of pits prior to ripping will be carried out where appropriate to determine specific requirements.

In General

i) All of the rehabilitated areas require either contour or grade ripping.

ii) Deep ripping should be done using a winged tyne to maximise subsoil fracture; batters and banks need not be deep ripped, but must be scarified or shallow ripped. This avoids bringing up rocks, but still controls erosion and prepares a seed bed.

iii) The distance between parallel riplines will depend on soil conditions, but must ensure a continuous fracture of the compacted subsoil.

iv) Ripping should be as deep as possible and should not be less than 1.2 metres.

v) Where soil erosion control provisions will not be compromised, the ground surface should be levelled wherever possible during or after deep ripping. Any alternative techniques which ensure erosion control while producing a smoother surface are to be encouraged.

vi) To avoid bringing up rocks, cleared, unmined areas should be scarified on contour.

7. WATER MANAGEMENT

7.1 Careful water management must be considered in every phase of the operation from initial clearing and road construction through to completion of rehabilitation.

7.2 A variety of water management systems may be adopted, depending on land use priority, site, and the nature of the specific catchment or storage facility.

7.3 Criteria for Success: irrespective of the system which is used, it must satisfy the following basic criteria:

- there must be a minimum of top soil erosion within pits;
- on proclaimed catchments, the system must meet standards of stream turbidity, salinity and biological purity defined by the Water Authority. Off proclaimed catchments, streams draining an area influenced by mining must not increase unduly in turbidity, chemical or biological pollution;
- there must be no long-term ponds of water lying either within or below pits or roads unless planned;
- the need for long-term maintenance must be minimal;
- peak flood levels should not be increased by mining in catchments such that they endanger dams on the catchment;
- the system must be acceptable in terms of costs, aesthetics and the land use priority.

7.4 Water Management Systems

Pits may be designed and constructed so as to:-

i) retain and infiltrate water; or

ii) discharge water.

A combination of retention and discharge techniques may be used. A recurrence interval of once in twenty years will be used as the rainfall design period.

7.4.1 Water retention and infiltration will be achieved by:-

i) infiltration and silt trapping in the contoured rip lines; and

ii) collection of overland flow, either in a series of midslope contour banks and a pit bottom sump, or by a system of grade discharge banks directing overland flow to predetermined sump areas within the pit.

Where used, contour intercepter banks will be constructed at up to 10 metre vertical intervals. Such banks may not exceed 1 metre in height nor have steep sides which present an obstacle to future access. Where specified, contour interception banks must be provided with suitably constructed overflows and non-erodible spillways. Construction of these devices must be completed before the first Autumn rains.

Grade discharge banks will connect to a stabilised waterway.

Well drained sites may require no engineered drainage structures.

Sump and drain locations will be indicated on the conceptual rehabilitation plans.

7.4.2 Water Discharge: Where this is prescribed it will be achieved by:

i) infiltration and silt trapping in the contoured or grade rip lines, and

ii) control of overland flow by grade banks, waterways and slow release detention ponds or filter systems.

Grade banks should be constructed so as not to erode, and to be located with a maximum 10 metre vertical interval. Distance apart should depend upon site characteristics and should be such that any potential erosion is contained between two grade banks, and does not create serious management problems such as accessibility, safety and loss of top soil.

Waterways should collect discharge from grade banks and deliver water to the discharge system. The discharge system from the detention pond or filter system should provide a major passageway for water; avoid long-term detrimental effects of silt and water on forest or stream vegetation; minimise forest soil erosion, and not significantly increase turbidity levels in forest streams. In addition in water catchment areas any discharge into the stream shall comply with the requirements of the Water Authority.

7.5 Unless planned, drainage from mine access roads, haul roads, mine site facilities or from pits must not flow uncontrolled into unmined dieback-free forest, but must be channelled (via ponds or filters) directly into the lowest part of the landscape at agreed locations.

7.6 All erosion control earthworks other than deep ripping with the winged tyne must be completed and effective before the first Autumn rains (i.e., generally before 30th April each year).

Winged tyne ripping effectively shatters the clay zone all year round.

Standards will be monitored and remedial action specified as appropriate and as agreed to by Alcoa/C.A.L.M. officers.

8. PLANTING

8.1 Planting Layout and Design

8.1.1 As a general rule, tree species will be established as mixtures. Monocultures may occasionally be planted in localised portions of the landscape.

In order to fulfil the widest range of rehabilitation objectives, the emphasis will be on species indigenous to the Darling Range.

Every mixture must include species indigenous to the Darling Range. Species mixes will be determined in advance and specified in the rehabilitation plan by C.A.L.M.

8.1.2 Plant spacing will be varied according to the detailed site rehabilitation objectives. In some areas such as at prominent view points or vistas and along selected areas of road, areas may be left unplanted. In other instances, trees may be planted in small groups or clumps to minimise the rigid plantation effect created by row planting on a regular spacing.

8.1.3 Stocking rate should be sufficient to yield good tree form. A minimum stocking of about 625 planted trees per hectare must be used. An increase in stocking to 1,250 stems per hectare is favoured to be achieved by the most economic and appropriate method, either broadcast seeding or planting. Where seeding is selected, objective stocking rate should be 2,500 s.p.h..

8.1.4 Do not plant trees in drainage channels.

8.1.5 Start planting in June when the soil is wet to depth. Cease planting by the end of the second week in August.

8.1.6 Seedling specifications: plants in jiffy pots or paper pots, at least 5-30 cm. in height with a minimum of 2 true pairs of leaves. Pots and soil mix sterile. Exposed roots to be trimmed before planting.

8.2 Before planting all pits will be inspected by C.A.L.M. officers. Parts of pits which are deemed by C.A.L.M. to be inadequately prepared, may not be planted until they are adequately prepared.

8.3 Access for planting crews must be pre-planned and specified so as to minimise traffic through unmined forest to minimise disease spread; and across the prepared pit to minimise erosion.

8.4 The C.A.L.M. District Manager must ensure a detailed record of species planted and treatments applied is made at the completion of the job.

8.5 <u>Selection of Tree Species for Planting</u>: Criteria for selection of tree species are:

i) Compatible with land use objectives specified in Regional Management plan
ii) Site suitability index
iii) Tolerance to dieback
iv) Fire resistance

v) Capacity for roots to penetrate the compacted kaolin layer
vi) Useful timber
vii) Proven species longevity, growth to maturity and regeneration in the mine pit environment

vii) Visual compatibility with indigenous forest
viii) Useful food and nectar sources for fauna

Following are the species to be used in bauxite mine rehabilitation in the western, high rainfall area:

Eucalyptus marginata
Eucalyptus calophylla
Eucalyptus patens
Eucalyptus megacarpa

The criteria for determining the distribution of the different species will be determined by position in the landscape and the risk and hazard of dieback disease. Risk and hazard will be determined by agreed procedures which are currently under development.

Alcoa staff and the C.A.L.M. District Manager will agree on a site by site application of the matrix when preparing conceptual plans.

Definitions of Risk and Hazard

Risk is an external force or agent that would bring *Phytophthora cinnamomi* (P.c.) to a site. Hazard is the degree to which conditions within the site favour the proliferation of the P.c. fungus once it has been introduced. The ability of plants to resist an infection is included as part of hazard rating.

8.5.1 Species Distribution Criteria

8.5.1.1 Assessing levels of dieback risk -

High - soil returned from moderate or high impact dieback area.

Moderate -

i) soil returned from low impact dieback area or high risk of dieback introduction.

ii) soil returned from non-dieback area, but little or no hygiene during soil handling.

Low - soil returned from non-dieback area and a high level of hygiene during soil handling.

8.5.1.2 Assessing levels of dieback hazard -

The dieback hazard of pits will be assessed by Alcoa and agreed with the C.A.L.M. District Manager. Hazard assessment will be according to a procedure to be agreed; based on ore depth, slope, aspect, soil type, pit location on the slope, position within the pit, ripping type, distance from the stream zone, etc., as appropriate. The system will be reviewed as required based on field experience.

8.5.1.3 Species Mix - Mine Pits (%)

Risk of P.c. Introduction	Dieback Hazard								
	Low			Moderate			High		
	Jarrah	Marri	Blackbutt	Jarrah	Marri	Blackbutt	Jarrah	Marri	Blackbutt
Low	80	20	0	60	20	20	20	20	60
Moderate	40	20	40	20	20	60	0	20	80
High	20	20	60	0	20	80	0	20	80

8.5.1.4 Species Mix - Significant Moisture Gaining Sites (e.g., stream crossings, pit sumps, pits with RL at level of adjacent Bullich zone).

Blackbutt - 50%
Bullich - 50%

8.6 Seed Sources for Seedlings

All seed to come from a range of provenances (locations to be approved by C.A.L.M.).

8.7 Fertilizer

Apply 200 grams of Diammonium phosphate per plant.

Fertilizer to be placed approximately 15 cms. from the base of the plant, in a spear hole or stamped depression.

8.8 Success Criterion for Planting/Fertilizer Operation

80% survival of planted species at 9 months after planting.

Areas of 0.5 hectares and above which fail to meet this criterion, to be rescheduled for replanting the next winter.

9. UNDERSTOREY ESTABLISHMENT

9.1 The aim of understorey establishment is to generate a diverse and vigorous understorey which will rapidly contribute to soil stabilization, erosion control and the build-up of soil nutrients and organic matter. At the same time, development of fuels and fire risks should be kept to tolerable levels.

9.2 Base species for the seed mix, comprising about 75% of the mixture, will include the major northern jarrah forest legume species. Jarrah seed is to be applied to all sites. The final mixture will be determined by agreement between Alcoa and the C.A.L.M. District Managers.

It will take into account such factors as seed availability and where the mixture will be used. A large diversity of minor jarrah forest species should make up the balance, including other nitrogen fixing species (*Allocasuarina* and *Macrozamia* spp.). Macrozamia seeds to be sown separately and pressed into the soil at a rate of 2 kilograms of seed per hectare.

9.3 Specific species and specific mixes should be applied to particular sites e.g., water logging tolerant species for sumps, wild flower species for roadsides and recreation areas (see Section 4.2), and species of low flammability and height for special fire management zones.

9.4 As a general rule, non-indigenous and high *Phytophthora cinnamomi* susceptible species should not be used. However, use of a low level of P.C. susceptible species (about 10 - 20 seeds) will provide for future dieback monitoring.

9.5 Understorey seed mixes will be determined in advance and specified in the rehabilitation plan for each pit and for specific sites within pits.

9.6 Fertilizer

Areas to be seeded will be broadcast fertilized with 450 kilograms per hectare of superphosphate.

9.7 Application Rate

Mixed understorey seed will be sown at the rate of 1 - 2 kilograms per hectare with the major legume seed mix no more than 1.0 kilograms per hectare.

Seeding is to be done after ripping by ground application and to be completed by 1st June each year.

9.8 Success Criterion

2 native plants established per square metre, 9 months after sowing, as determined by stocked quadrat survey of each pit.

Areas of 0.5 hectares or greater not stocked at this rate to be reseeded the following Autumn. Light scarification and control of insect predation may be necessary to promote seed germination in areas reseeded in Year 2.

10. ROADS

10.1 The road network which remains after rehabilitation must conform to a predetermined plan. The basic planning principle is to aim for the minimum number of well surfaced roads low in the landscape consistent with provision for public access and fire protection.

10.2 This plan will be drawn-up from approved 5 year mining plans, and will cater for -

i) access for mining

ii) access for rehabilitation

iii) access for future forest and catchment management including fire protection.

10.3 Unwanted roads will be rehabilitated by:

i) if possible and economical recovery of gravel for reuse elsewhere

ii) blasting of caprock and/or breakup of all compacted material

iii) overburden and top soil return

iv) ripping and erosion control

v) seeding and planting in harmony with surrounding forest

11. PRESCRIPTION REVIEW

Next date for review of this prescription : July, 1989.

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