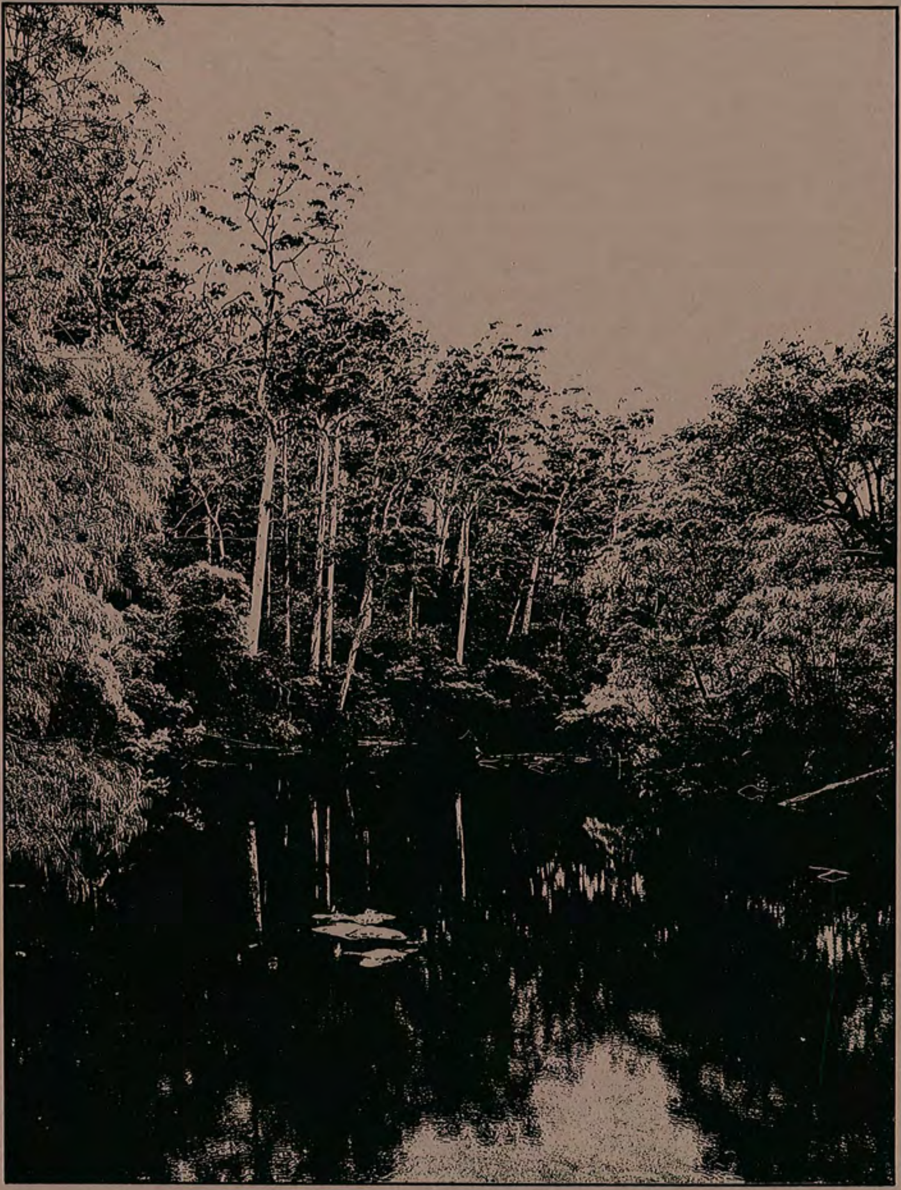
Stream and Ground water Response to Logging and Subsequent Regeneration in the Southern Forest of Western Australia

Results from four catchments

by H. Borg, G.L. Stoneman and C.G. Ward



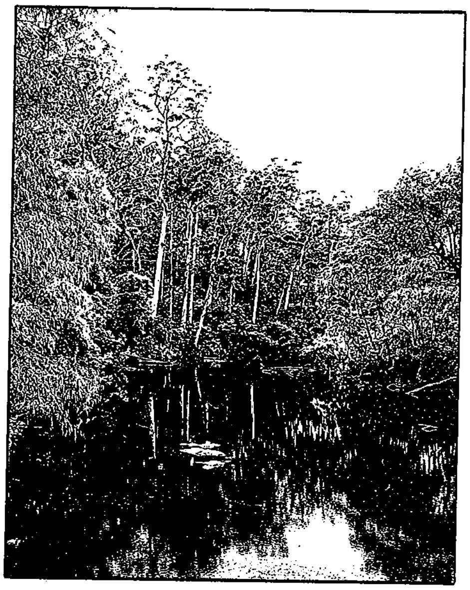
Technical Report No 16

April 1987

Department of Conservation and Land Management W.A.

Stream and Ground water Response to Logging and Subsequent Regeneration in the Southern Forest of Western Australia

Results from four catchments



by

H. Borg
Water Authority of WA,
John Tonkin Water Centre,
Newcastle Street, Leederville, Western Australia.

G.L. Stoneman
Department of Conservation and Land Management,
Del Park Road, Dwellingup, Western Australia.

C.G. Ward
Department of Conservation and Land Management,
Brain Street, Manjimup, Western Australia.

Technical Report No 16

April 1987

Published by the
Department of Conservation and Land Management W.A.

ISSN 0816-6757

CONTENTS

Figures

Tables

SUMMARY

1) Four small catchments (Crowea, Poole, Iffley and Mooralup) were selected in 1975 to study the effect of heavy selection cutting or clear-felling and subsequent regeneration on streamflow, stream salinity and ground water levels in the southern forest of Western Australia. The catchments were chosen to represent a combination of rainfall, forest type, soils and topography found in the region. They were logged between November 1976 and March 1978. Regeneration began one to 30 months after the completion of logging. The regrowth of the vegetation in these catchments and some other areas which had experienced heavy selection cutting or clear-felling since the 1880s was assessed in 1986 as part of a related investigation by Stoneman et al. (1987), but some of the results are also presented here.

2) During the study period (1976 through 1985) the annual rainfall in the research area was generally below the mean for 1926 through 1976. These dry conditions probably influenced the magnitude and duration of the hydrologic response to logging and subsequent regeneration, but not the general trends. This should be considered if the results from this research are applied in times of higher rainfall.

3) As a result of logging annual streamflow volumes increased for two years (1977 and 1978) and then gradually declined again as the vegetation regenerated. Although the trends are somewhat obscured by the influence of annual variations in rainfall, it appears that by about 1990, 11 to 12 years after the beginning of regeneration, the annual streamflow volumes will be back to their pre-logging values. In the Mooralup catchment, where streamflow volumes are naturally small due to the low annual rainfall and high potential evapotranspiration, this may have happened by 1985.

4) Flow-weighted mean annual stream salinities reached their highest level one to three years after logging and have declined since. The largest observed increase was 94 mg/L TSS. Even at their highest level flow-weighted mean annual stream salinities were below 500 mg/L TSS which is considered to be the upper limit for high quality drinking water. Throughout the study period, the lowest values were observed in the Mooralup catchment, despite its location in the low rainfall zone, which prior to this study was considered to be the most likely region where logging might lead to high stream salinities. When streamflow and ground water, which determine stream salinity, have attained the level they would have been at without logging, stream salinity should do the same. This has probably already happened in the Mooralup catchment, and is likely to happen in the early 1990s in the other three catchments.

5) Ground water levels rose for two to four years after logging and then started to fall again. Although changes due to annual variations in rainfall and evapotranspiration could only partially be accounted for due to the lack of accurate calibration with control bores, it seems that by 1991, 12 to 13 years after the beginning of regeneration, ground water levels will reach the values they would have been at had there been no logging.

6) The overstorey cover in regenerating karri stands reached the density of unlogged stands after some ten years of growth, continued to increase for another ten years and then stabilised at a higher value than is typical for unlogged stands. Total vegetation cover reached the unlogged value within five years, rose for five more years and since remained above the unlogged value. In jarrah regrowth areas overstorey and total vegetation cover exceeded 70 per cent of the value for unlogged forest within five years after regeneration, 90 per cent within ten years, and reached the unlogged level in 20 to 30 years.

1. INTRODUCTION.

It had long been recognised that the permanent removal of the native perennial vegetation and its replacement with annual crops and pastures can lead to large and persistent salinity increases in the streams of south-west Western Australia (Wood 1924; Burvill 1947; Peck and Hurle 1973). However, little was known quantitavely about the influence of logging and subsequent regeneration on stream salinity.

For a variety of reasons the (then) Forests Department of Western Australia changed its logging system in the southern forest from relatively light selection cutting to clear-felling of karri stands in 1967, and to heavy selection cutting of jarrah stands in 1970. As under the former system, all cut-over areas were regenerated to forest.

Heavy selection cutting and clear-felling, both followed by regeneration of the cut-over areas to forest, had been practised before in the southern forest from the late 1920s to about 1940. No obvious effect on stream salinity was noted then. However, no specific attempt was made to monitor any possible effect. The scientific community was just beginning to uncover the connection between increases in stream salinity and clearing for agriculture. Consequently, logging and subsequent regeneration to forest, a temporary and less severe hydrologic disturbance than clearing for agriculture, was not perceived to affect stream salinity.

By the early 1970s the effect of agricultural clearing on stream salinity was more firmly established and the public began to become aware of the problem. Heavy selection cutting and clear-felling are a more significant hydrologic disturbance than light selection cutting so that their re-introduction raised some concern about their influence on stream salinity (Forests Department of Western Australia 1973). In 1973 the West Australian Minister for Conservation and Environment therefore arranged the formation of a Steering Committee to conduct research into the effects of the revised cutting strategies on the water resources in the southern forest. The Steering Committee initiated a number of research projects which were then conducted by various government departments (Steering Committee 1978, 1980). The Public Works Department of Western Australia (which in 1985 became part of the Water Authority of Western Australia) in co-operation with the Mines Department of Western Australia and with some assistance from the Commonwealth Scientific and Industrial Research Organisation, Division of Soils, was given the task to undertake several paired catchment studies. These studies commenced in 1975. In order to collect some data under natural forest conditions for calibrating the hydrologic response of the paired catchments, logging could not be carried out until 1982. A third progress report on this research has recently been prepared (Borg *et al*. 1987).

Since results from the paired catchment studies could not be expected until well into the 1980s, the Forests Department of Western Australia (which in 1985 became part of the Department of Conservation and Land Management W.A.) with assistance from the Mines Department of Western Australia was asked to conduct similar but less sophisticated studies at the same time. Their objective was to provide an early indication of the stream and ground water response to logging and subsequent regeneration under the revised cutting strategies. Four small catchments in the southern forest were equipped for recording rainfall, streamflow, stream salinity and ground water levels. They were logged between November 1976 and March 1978 after one year of hydrologic observation and then allowed to regenerate. All of the above parameters were gauged until the end of 1985 when, due to limited funds, data collection was reduced to the monitoring of ground water levels.

The information obtained from these four catchments between 1975 and 1986 inclusive is analysed in this report. To aid the understanding of the results, their presentation is preceded by a description of the research area and its hydrology. A chapter on the recovery of the vegetation cover after logging is presented after the results section. The data in this chapter were extracted from a related study by Stoneman _et_ _al_. (1987).

This report was prepared under the direction of the Forest Management Sub-Committee of the West Australian Steering Committee for Research on Land Use and Water Supply.

2. DESCRIPTION OF THE RESEARCH AREA

2.1 Location, climate and vegetation

The southern forest of Western Australia is defined as the forested land in the State which drains into the Southern Ocean. The change from light selection cutting to heavy selection cutting and clear-felling was implemented in an area of 884 100 ha around the town of Manjimup. This part of the southern forest has since been referred to as the Woodchip Licence Area (Fig. 1, see inside back cover). The research discussed here was conducted in this area.

Mean annual rainfall in the area ranges from over 1400 mm in the south-west to less than 700 mm in the north-east (Fig. 2). Most of it arises from low pressure systems moving across the region from a westerly direction. About 80 per cent of the annual precipitation occurs from May through October. The mean annual pan evaporation varies from 1150 mm in the south-west to 1450 mm in the north-east (Fig. 3). (Pan evaporation is a rough estimate of potential evapotranspiration. Potential evapotranspiration is defined as the amount of water which can be removed by evaporation, transpiration or a combination of both from an area which has an unrestricted supply of water.) In contrast to rainfall, pan evaporation is lowest in winter and highest in summer. As a result there is a water excess in winter when rainfall exceeds pan evaporation, and a water deficit in summer when pan evaporation exceeds rainfall. This is illustrated in Figure 4 together with other climatic characteristics of the region. Rainfall decreases with distance from the coast while pan evaporation increases with distance from the coast. Consequently, the water excess in winter decreases with distance from the coast and the water deficit in summer increases with distance from the coast.

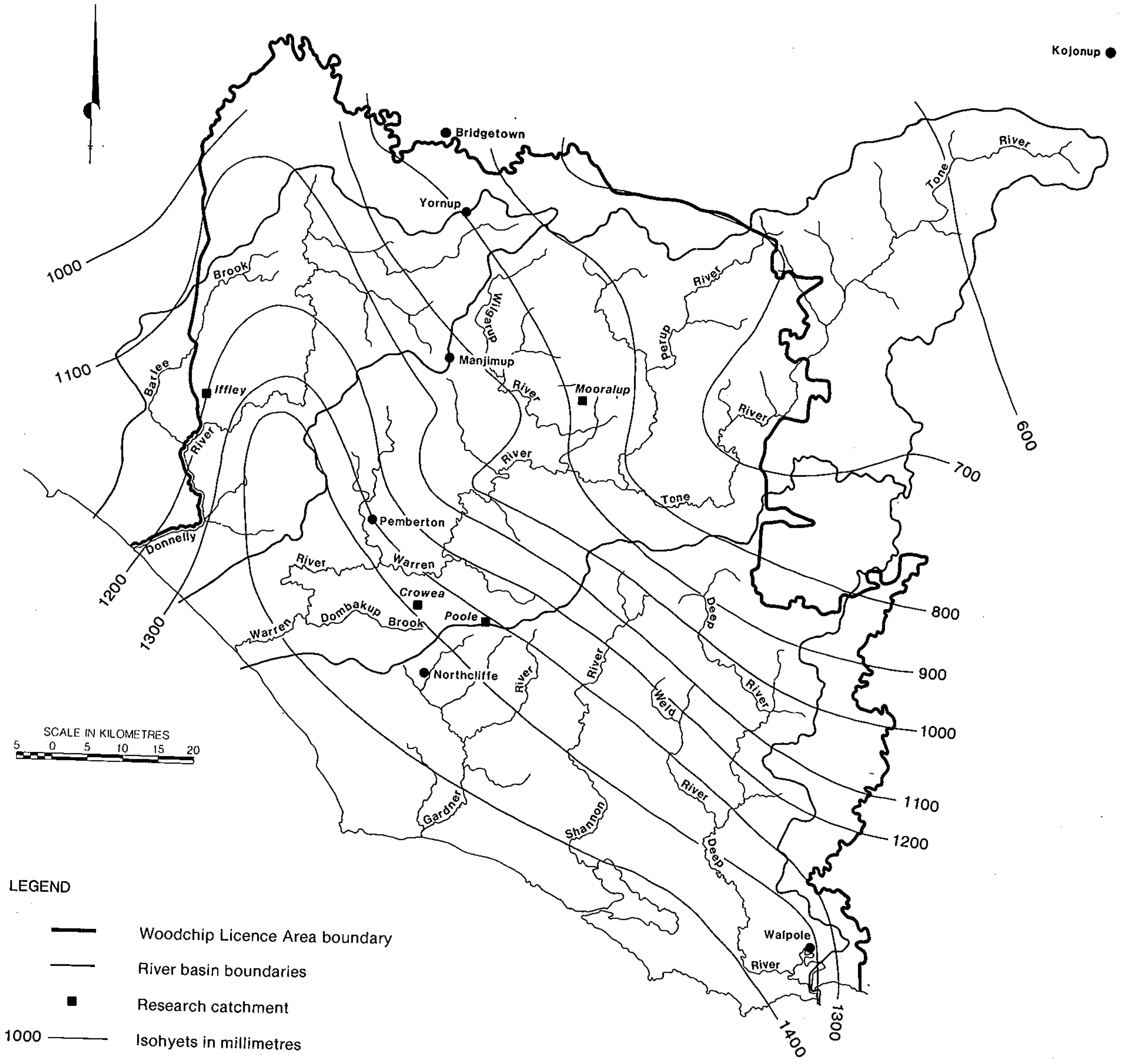


Figure 2
Mean annual rainfall in the research area. (Data from Loh and King 1978.)

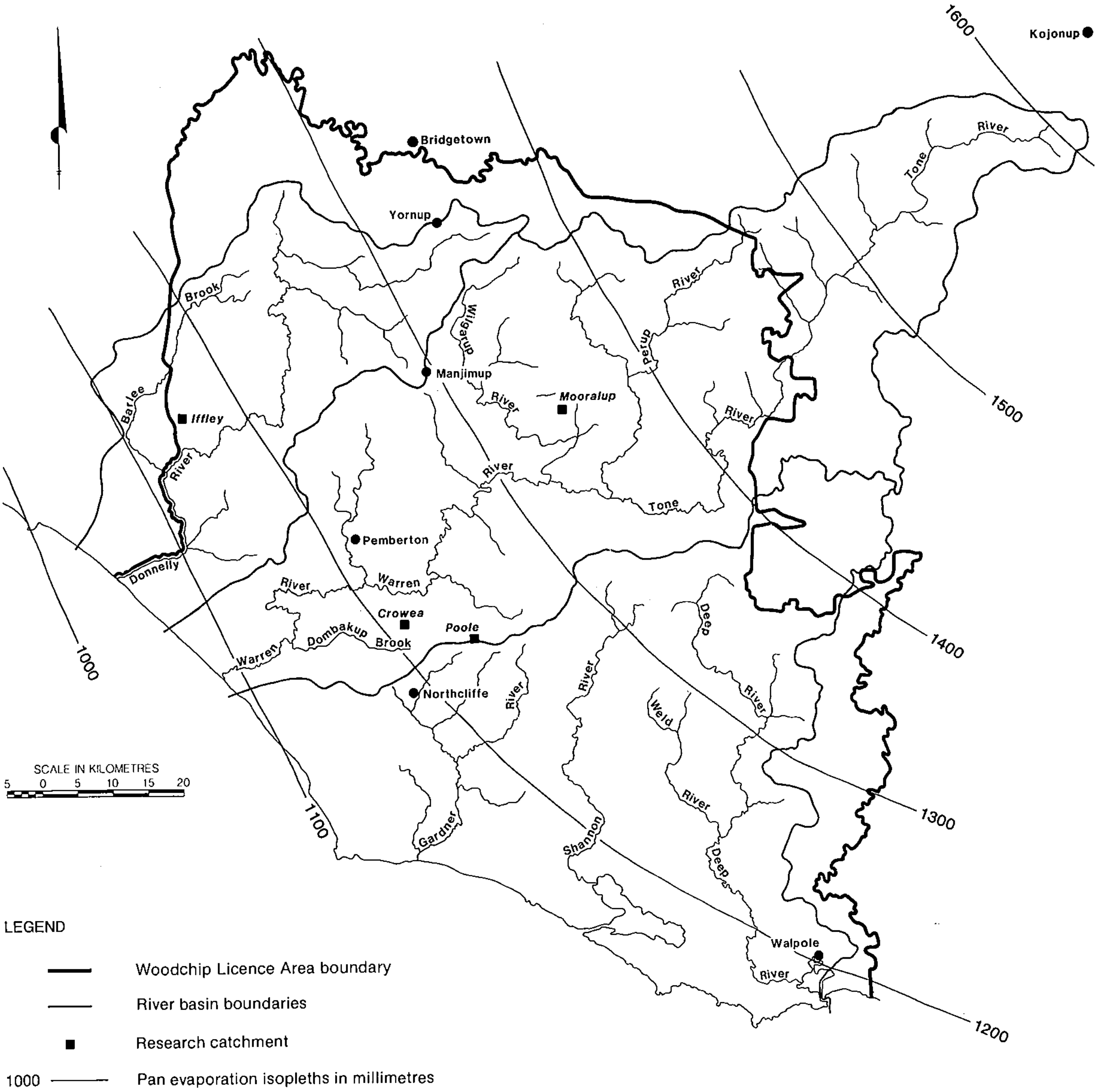
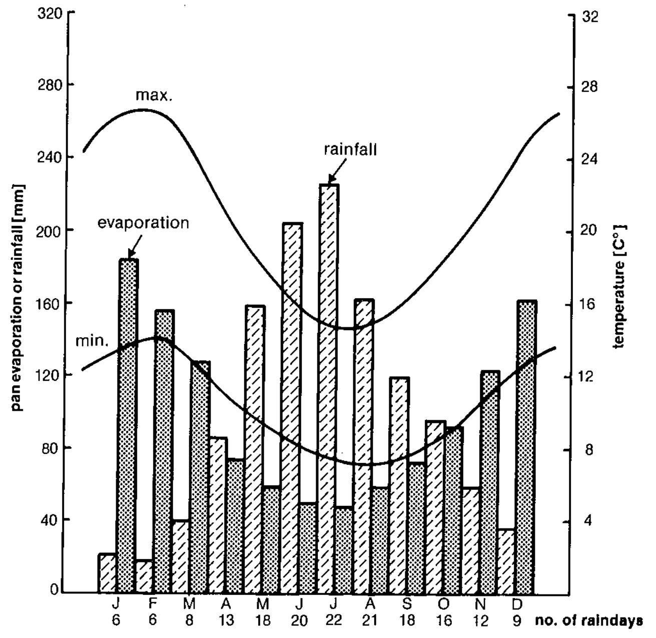


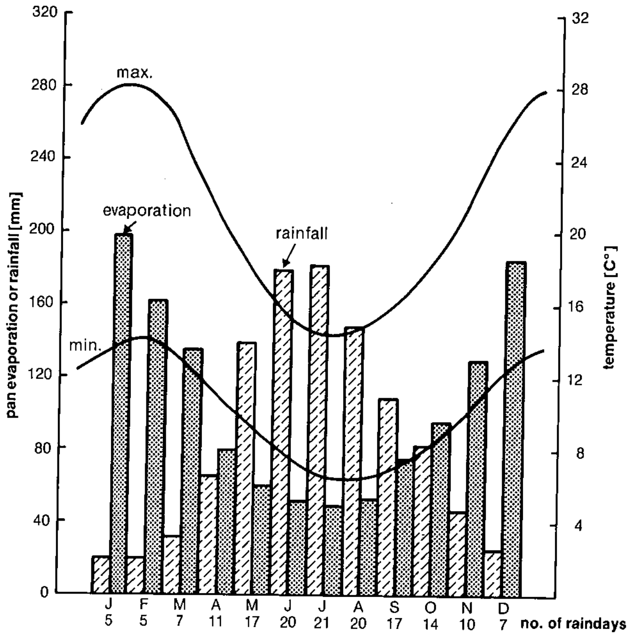
Figure 3

Mean annual pan evaporation in the research area. (Based on Commonwealth Bureau of Meteorology data to the end of 1985.)

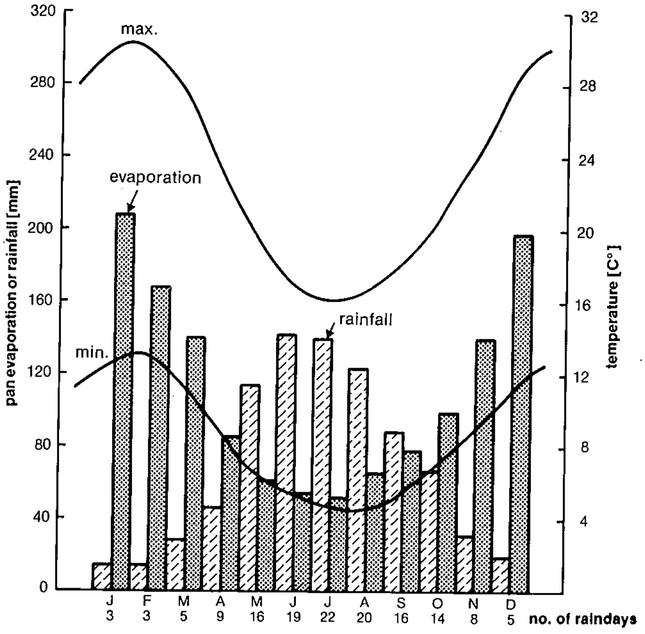
Pemberton:	
elevation	174 m
average annual pan evaporation	1207 mm
average annual rainfall	1228 mm
average number of raindays per year	169
average maximum temperature	20.1°C
average minimum temperature	10.2°C



Manjimup:	
elevation	280 m
average annual pan evaporation	1285 mm
average annual rainfall	1047 mm
average number of raindays per year	154
average maximum temperature	20.5°C
average minimum temperature	9.9°C



Bridgetown:	
elevation	150 m
average annual pan evaporation	1348 mm
average annual rainfall	847 mm
average number of raindays per year	140
average maximum temperature	22.5°C
average minimum temperature	8.2°C



Kojonup:	
elevation	305 m
average annual pan evaporation	1636 mm
average annual rainfall	542 mm
average number of raindays per year	123
average maximum temperature	21.2°C
average minimum temperature	9.4°C

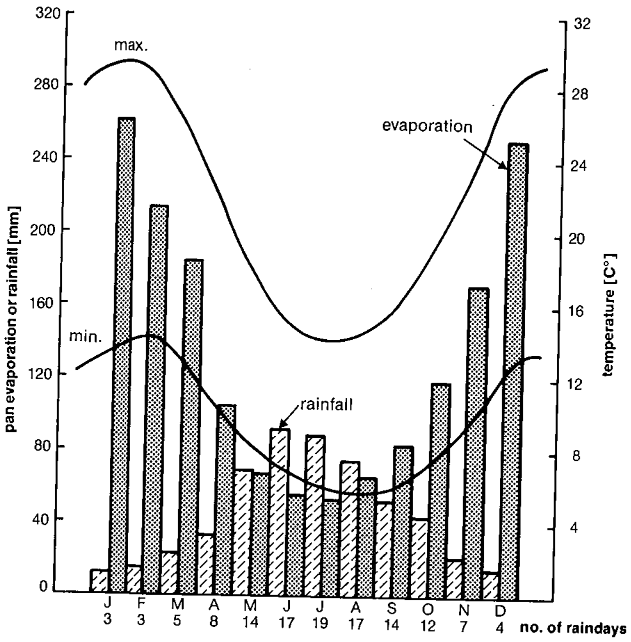


Figure 4

Climatic characteristics of four locations in or near the research area. (Rainfall and temperatures based on Commonwealth Bureau of Meteorology data to the end of 1981, pan evaporation based on Commonwealth Bureau of Meteorology data to the end of 1985.)

Within the area are 176 600 ha of karri forest and 418 800 ha of jarrah forest (Table 1). This represents about 94 per cent of all karri forest and about 20 per cent of all jarrah forest in the State. Karri (Eucalyptus diversicolor) is the principal species where the mean annual rainfall exceeds 1100 mm. It does not occur where the mean annual rainfall is less than 1000 mm (Churchill 1967) and is virtually restricted to loamy soils. Jarrah (Eucalyptus marginata) dominates areas with 1100 to 650 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 population occurs in pure stands, and the remainder in association with marri (Eucalyptus calophylla). Most of the jarrah stands contain marri. The proportion of marri in jarrah and karri forest varies between sites, but is often as high as 50 per cent (Forests Department of Western Australia 1973). A detailed description of the vegetation in the region is given by Smith (1972), and Bradshaw and Lush (1981).

Table 1: Vegetation types and area by land tenure in the research area as at December 1986. (Data from the FMIS data base of the Department of Conservation and Land Management W.A.)

Tenure	Vegetation type				
	karri forest [ha]	jarrah forest [ha]	other[1] [ha]	cleared [ha]	total [ha]
Crown land managed by the Department of Conservation and Land Management[2]	165 900	393 900	156 100	1 700	717 600
Crown land managed by Shires	600	1 400	800	1 500	4 300
Crown land managed by other Government organisations	200	800	1 400		2 400
Private property	9 900	22 700	17 600	109 600	159 800
TOTAL	176 600	418 800	175 900	112 800	884 100

[1] mostly coastal heath and shrubs
[2] includes freehold land held in the name of the Executive Director

Some 109 600 ha of land in the area are cleared for agriculture. Roughly 90 per cent of that is under pasture for grazing cattle and sheep. The remaining 10 per cent produces cereals and a variety of horticultural crops, such as beans, potatoes, cauliflower, onions and peas.

2.2 Forestry

Logging in the area began in the early 1900s and was then largely associated with clearing for agriculture. Planned logging for timber production with subsequent regeneration of the cut-over areas commenced in the late 1920s, under the supervision of the newly created Forests Department, to stop the exploitation and destruction of the forest and to ensure sustainable timber yields for the future.

Karri naturally often occurs in fairly even-aged stands which are the result of regeneration after the previous stand was killed by fire (Mount 1964). Mature even-aged stands are suited for clear-felling since they generally contain a large volume of marketable timber per unit area. Furthermore, the growth of karri seedlings is severely suppressed by the presence of older vegetation (Rotheram 1982). After clear-felling regeneration is vigorous because development of the young trees is then not inhibited by competition from older growth for light, nutrients and water. This had been demonstrated by the prolific regeneration of karri stands near Denmark and Boranup which were clear-felled in the 1880s. Karri areas were therefore initially clear-felled, the good timber removed and the remainder burnt as waste. However, several factors led to a change to selective cutting by the 1940s.

The aim of logging was to produce sawlogs, most of which were then processed to make high quality products for export. Since any small or defective trees and most of the marri trees, regardless of size, did not meet the sawlog standards adopted by the timber mills at the time, clear-felling generated a lot of waste.

- As more forest was assessed, it became apparent that many large karri trees were dying due to old age or fire damage. Under a lighter cutting regime where fewer trees were removed per unit area, more forest would be accessed and much of this timber could be salvaged before it became useless. The roads and railways built in the process would provide the infrastructure for the beginnings of a fire protection system.

- Felling and disposing of trees with no commercial value costs money. During the economic depression of the 1930s this could be done at relatively low cost due to the abundance of cheap labour. However, cheap labour became scarce at the start of the Second World War.

- There was pressure to release clear-felled areas for agriculture since to the layperson they appeared to be devastated and of no future value to forestry. Retaining trees created the impression that the area was still growing useful trees and relieved most of this pressure.

Young jarrah and marri trees also grow better in the absence of older growth. They are less effected by the presence of older vegetation than young karri and can thus develop into mature trees. Hence jarrah forest naturally contains a wider range of tree ages and sizes. Mixed-aged stands contain a relatively small amount of marketable timber at any given time and are suited for selective cutting where marketable older trees are removed and young ones retained for future harvesting. Jarrah stands were therefore always cut selectively for sawlogs. However, marri in general and jarrah unsuited for sawlogs were often ringbarked or felled to promote the growth of trees retained for future sawlog harvesting. This practice continued until the beginning of the Second World War when cheap labour became unavailable. Since then only selective cutting of sawlog quality trees was carried out. Additional information on the history of logging in the southern forest is given by White and Underwood (1974), Collins and Barrett (1980), and Bradshaw and Lush (1981). A helpful explanation of forestry terminology is given by McKinnell (1982).

Selective cutting for sawlogs poses a number of problems in karri as well as jarrah forest:

- The waste from logging is burnt because it is a fire hazard, because it would otherwise impede regeneration, and because nutrients released from the resulting ashbed enhance growth. However, retained trees are frequently injured during such burns. This is especially problematic in karri stands. An intense fire is required to prepare a good seedbed for the germination of karri seeds, but karri trees, young ones in particular, are rather sensitive to fire. Jarrah and marri are more fire tolerant. Also, their cut-over stands regenerate mostly from lignotuberous advance growth. Because this does not require an ashbed, a less intense burn is sufficient.

- Increased exposure to wind often damages retained trees.

- Competition from retained trees generally slows the regeneration of cut-over areas.

- Regrowth is frequently damaged during the felling and removal of trees in future logging operations or subsequent waste-disposal burns.

- Good timber is continuously removed while trees unsuitable for sawlogs are left standing. This gradually lowers the productivity of a stand because the non-sawlog quality trees occupy space which could be filled by more productive trees, and because they retard regeneration.

All these factors contribute to a continuous reduction in timber yield from a selectively cut forest. To obtain the same amount of timber in the future a larger area would have to be cut. This is not desirable ecologically because it would disturb more flora and fauna habitats and, in jarrah forest, increase the risk of spreading the root fungus Phytophthora cinnamomi which causes jarrah dieback, nor economically since the wider spread of logging operations would incur more road construction, hauling and supervision.

An alternative to expanding the cut-over area is to increase the productivity of a forest by removing non-sawlog quality trees which occupy useful growing space and inhibit the development of young trees. To achieve this and to overcome the other disadvantages of selective cutting the Forests Department returned to clear-felling of karri stands in 1967. As most of the southern forest had been dedicated as State forest by then, it was no longer necessary to retain trees to avoid pressure to release clear-felled areas for agriculture. Also, as a consequence of marketing efforts by the Forests Department, timber mills now accepted smaller karri trees for sawlogs, which reduced the amount of waste generated by clear-felling. The silvicultural management of karri forest is discussed in detail by White and Underwood (1974), Bradshaw and Lush (1981), and Bradshaw (1985).

Mainly to reduce the area cut-over each year, and thus to reduce the risk of spreading jarrah dieback without a proportional reduction in timber yield, the Forests Department decided in 1970 to move to a much heavier selective cutting of jarrah forest for sawlogs. However, removal of marri and non-sawlog quality jarrah was to take place as well to improve the regrowth of logged areas and hence the productivity of the regenerating forest. The intensity of the resulting cut depends on the size and age distribution of the trees in the stand to be logged and may range from light thinning to clear-felling. This is very similar to the cutting regime followed between the late 1920s and the beginning of World War Two. For an in-depth review of silviculture of jarrah areas in the southern forest refer to Bradshaw (1986).

The Forests Department always did, and now as part of the Department of Conservation and Land Management still does, seek uses and markets for non-sawlog quality timber to achieve a better utilisation of the wood resources in a forest. Trees unsuitable for sawlogs can often be chipped and turned into wood pulp for paper production. Sawmill residues can also be recycled for woodchips. Operating a woodchip mill in Western Australia was first suggested in 1899 and contemplated several times since, but could not be realised due to the lack of a market for woodchips. After the decision to change from relatively light selection cutting in general to heavy selection cutting of jarrah stands and clear-felling of karri stands the establishment of a woodchip mill was considered again as a means to utilise some of the timber not suitable for sawlogs which would otherwise be burnt as waste. In the early 1970s a market for woodchips was found in Japan, and the newly founded West Australian Chip and Pulp Company finally opened a woodchip mill near Manjimup in 1975.

The establishment of a chipmill made some aspects of forest management more economical. Revenue could now be earned from marri trees and non-sawlog quality karri trees which previously had been cut down and burnt as waste at an expense, or left standing in which case they occupied useful growing space and slowed regrowth. Also, thinning of young regenerating stands could now provide some income since their thinnings are usually too small for poles or sawlogs, but suitable for chipwood. Regenerating stands are often densely stocked. After several years of growth this results in strong competition for resources between individual trees and slows the advance of the stand. A thinning operation at this time salvages trees which would eventually die due to competition, and boosts the growth of retained trees by reducing competition. Even-aged karri and karri-marri regrowth stands are especially suited for thinning since they yield a large amount of chipwood.

In other states of Australia some forests are cut primarily to obtain chipwood. The primary objective of all logging operations in Western Australia is to supply sawlogs. With clear-felling only wood which would otherwise be burnt as waste is taken away for chipping. With selection cutting only trees which will not yield sawlogs and if left standing would suppress regeneration or occupy useful growing space are removed for woodchips. The logging operations are supervised by the Department of Conservation and Land Management. All suitable material must be processed for sawlogs and is not permitted to be chipped. This is in the interest of the Department of Conservation and Land Management as well as the forest industry since sawlogs bring in more revenue than woodchips.

From its re-introduction in 1967 until the opening of the chipmill in 1975, clear-felling was concentrated in pure karri stands with a high proportion of sawlog quality timber. Where marri was encountered early in this period it was felled and burnt as waste. Towards the end of the period when the opening of the chipmill was impending, marri was left standing and regeneration of the cut-over area delayed so that it could be removed for chipwood later. Until the opening of the chipmill jarrah forest was only cut selectively for sawlogs and no marri was felled. Felling of marri commenced after the chipmill was opened.

Table 2 lists the sawlog and chipwood production since 1975. Most marri trees contain an abundance of gum veins and gum rings. After a tree is felled the gum dries out and the wood disintegrates along those veins and rings. Hence marri cannot generally be used for sawlogs and provides the bulk of the chipwood. However, some marri stems have sufficiently few gum veins and rings to be suited for sawlogs and are then processed as such. Most karri trees are fit for sawmilling so that only material too small or defective for sawlogs is released for chipping. Jarrah provides only sawlogs because it yields too little cellulose and requires a relatively high amount of pulping chemicals to be economical for paper production (Fallick 1987).

2.3 Water resources

The southern forest contains most of the Shannon, Warren and Donnelly River basins. (By definition the Shannon River basin includes the Gardner, Deep and Weld Rivers.) These basins generate an average annual streamflow of 1550×10^6 m^3 of which 720×10^6 m^3 are readily divertible (Collins and Barrett 1980). This represents 39 per cent of all surface water resources and 27 per cent of the combined surface and ground water resources in south-west Western Australia. Less than one per cent of that is currently used for public water supplies.

The National Health and Medical Research Council (NH&MRC) in conjunction with the Australian Water Resources Council (AWRC) regards 1500 mg/L TSS (total soluble salts) as the maximum salinity level for drinking water of satisfactory quality and considers water with less than 500 mg/L TSS to be of excellent quality (Department of Health 1980). These guidelines are currently under review. A draft version of this review (NH&MRC/AWRC 1986) states that a change in taste may be detected at chloride concentrations above 400 mg/L. For the

Table 2: Areas cut-over and timber volumes extracted from Crown land in the Woodchip Licence Area between 1976 and 1985. (Data from Department of Conservation and Land Management records).

Year	Area cut-over [ha]					Timber volumes extracted							
	jarrah forest		karri forest			Sawlogs [m^3]			Chipwood [m^3]				
	saw-logs[1]	chip-wood[2]	saw-logs[1]	chip-wood[2]	regrowth thinned	jarrah	marri	karri	jarrah	marri	karri	karri regrowth thinnings	sawmill residues
1976	6 470	-	3 520	1 850	-	148 000	3 400	300 500	-	169 000	103 000	-	26 400
1977	5 880	140	2 050	2 690	-	156 800	8 400	264 000	-	313 600	111 000	-	51 100
1978	4 550	320	2 660	3 220	-	160 300	9 800	280 700	-	317 200	100 400	-	86 600
1979	2 760	1 160	2 280	2 580	-	138 300	10 200	269 500	-	414 800	92 000	-	97 300
1980	3 440	2 120	2 040	2 310	140	177 100	8 200	260 900	4 900	444 300	125 000	11 500	74 000
1981	4 120	1 450	1 450	1 580	250	182 500	8 200	239 500	-	308 700	100 300	22 900	61 700
1982	4 220	820	1 220	1 330	260	167 600	7 600	206 300	-	263 800	78 500	22 500	56 900
1983	3 200	890	1 730	1 520	270	108 600	6 700	201 700	-	273 200	101 600	25 000	69 800
1984	3 150	2 100	2 120	2 500	390	117 000	10 900	250 600	-	382 000	74 100	25 300	64 000
1985	4 560	2 640	1 530	1 610	320	229 200	16 100	222 600	-	417 400	68 000	27 300	72 200

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

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

ionic composition of surface waters in south-west Western Australia (Loh et al. 1983) this corresponds to 700 to 800 mg/L TSS. Up to 1000 mg/L TSS are generally acceptable, but levels up to 1500 mg/L can be accepted where better quality water cannot be procured at reasonable cost.

Table 3 gives the flow-weighted mean annual salinity for several streams in the research area. The available record from 1960 to 1985 for some of them is plotted in Figure 5. (Flow-weighted mean annual stream salinity is the value that would be obtained if all water which flows past a given point in a year were collected, mixed and its salinity measured.) Streams draining completely forested catchments (Table 3) generally have a flow-weighted mean annual salinity between 100 and 200 mg/L TSS. Salinity is inversely proportional to streamflow volume and can decrease by 50 to 100 mg/L TSS in years of above average streamflow or increase by the same amount when streamflow is below normal as illustrated by the Weld River, Shannon River and Barlee Brook in Figure 5. Bigger increases are possible in years of very low flow, especially in areas with high soil salinities as shown by the Yerraminnup Creek. Stream salinity also varies within a year. On days of low streamflow it may reach 500 mg/L, or more where soil salinity is high. On days of high streamflow, stream salinity is often less than 100 mg/L.

Small streams like Carey Brook, the tributaries of Easter and Quininnup Brooks, or Four Mile Brook are generally located in relatively flat valleys high in the landscape. Larger streams flow in more incised valleys lower in the landscape where soil salinity is higher (Johnston et al. 1980). As a result larger streams tend to have somewhat higher salinities. On the other hand, the catchments of the aforementioned small streams have never been logged, or in the case of Four Mile Brook not since 1940, while logging has taken place and is still going on in the catchments of the larger streams. How much, if any, of the difference in stream salinity may be due to logging rather than

Table 3: Flow-weighted mean annual salinities of several streams in the research area. (Data from the CONREC data base of the Water Authority of Western Australia, Collins and Barrett 1980, and Public Works Department of Western Australia 1982.)

Stream	Gauging station number[1]	Catchment area [km²]	Range of mean annual rainfall in catchment [mm]	Average mean annual rainfall in catchment [mm]	% of catchment cleared for agriculture	% of total agricultural clearing located in each rainfall zone			Flow-weighted mean annual stream salinities [mg/L TSS]				Years of record
						high	intermediate	low	mean	s.d.[2]	max.	min.	
Carey Brook (Staircase Road)	608002	41	1350-1450	1420	0	0	0	0	116	11	134	90	1974-1986
Carey Brook (Lease Road)	608006	2.7	1350-1420	1400	0	0	0	0	102	10	123	92	1976-1985
Weld River	606195	240	1080-1370	1250	0	0	0	0	163	24	228	119	1964-1985
Easter Brook tributary	607004	1.3	1240	1240	0	0	0	0	111	11	130	90	1976-1985
Four Mile Brook	607014	13	1180-1250	1220	0	0	0	0	125	11	145	111	1979-1986
Shannon River	606185	350	880-1440	1195	2.5	100	0	0	159	27	231	127	1964-1985
Barlee Brook[3]	608001	164	1120-1240	1170	0	0	0	0	152	23	220	112	1962-1985
Quinninup Brook tributary	607012	1.8	1080	1080	0	0	0	0	109	15	140	86	1976-1985
Deep River	606001	458	800-1280	990	0	0	0	0	177	28	222	127	1975-1985
Yerraminnup Creek	607005	2.5	850	850	0	0	0	0	160	73	317	94	1975-1985

Dombakup Brook	606155	114	1370-1450	1425	15.7	100	0	0	148	27	237	119	1961-1985
Fly Brook	608171	67	1330-1450	1415	25.0	100	0	0	142	15	182	117	1962-1985
Gardner River	606218	419	1110-1450	1410	16.5	100	0	0	159	29	220	127	1966-1985
Lefroy Brook[4] (Rainbow Trail)	607013	254	1070-1410	1220	30.0	90	10	0	179	20	228	143	1943-1986
Scabby Gully	607052	10	1150-1180	1165	8.0	100	0	0	162	16	204	138	1956-1986
Lefroy Brook (Channybearup)	607002	92	1070-1200	1130	55.0	84	16	0	270	42	352	195	1970-1986
Donnelly River	608151	808	770-1420	1110	21.5	20	65	15	206	28	262	137	1956-1985
Smith Brook	607600	.5	990	990	100.0	0	100	0	298	48	438	250	1970-1984
Wilgarup River	607144	450	790-1040	915	32.0	0	76	24	861	280	1652	385	1960-1985
Warren River (Barker Road)	607220	4040	550-1450	865	32.8	12	17	72	716	160	966	456	1966-1985
Perup River[5]	607004	645	680-890	765	18.5	0	0	100	2797	1530	5559	572	1961-1985
Warren River (Wheatley Farm)	607003	2910	550-1040	735	36.4	0	11	89	2104	675	3130	1076	1970-1985
Tone River	607007	1040	550-710	630	65.5	0	0	100	3956	2683	7902	1426	1978-1984

---

[1] gauging station locations are given in Appendix A

[2] s.d. = standard deviation

[3] record prior to 1972 from gauging station 608148 nearby which was closed in 1973

[4] record prior to 1979 from gauging station 607009 nearby which was closed in 1981

[5] record prior to 1974 from gauging station 607145 nearby which was closed in 1975

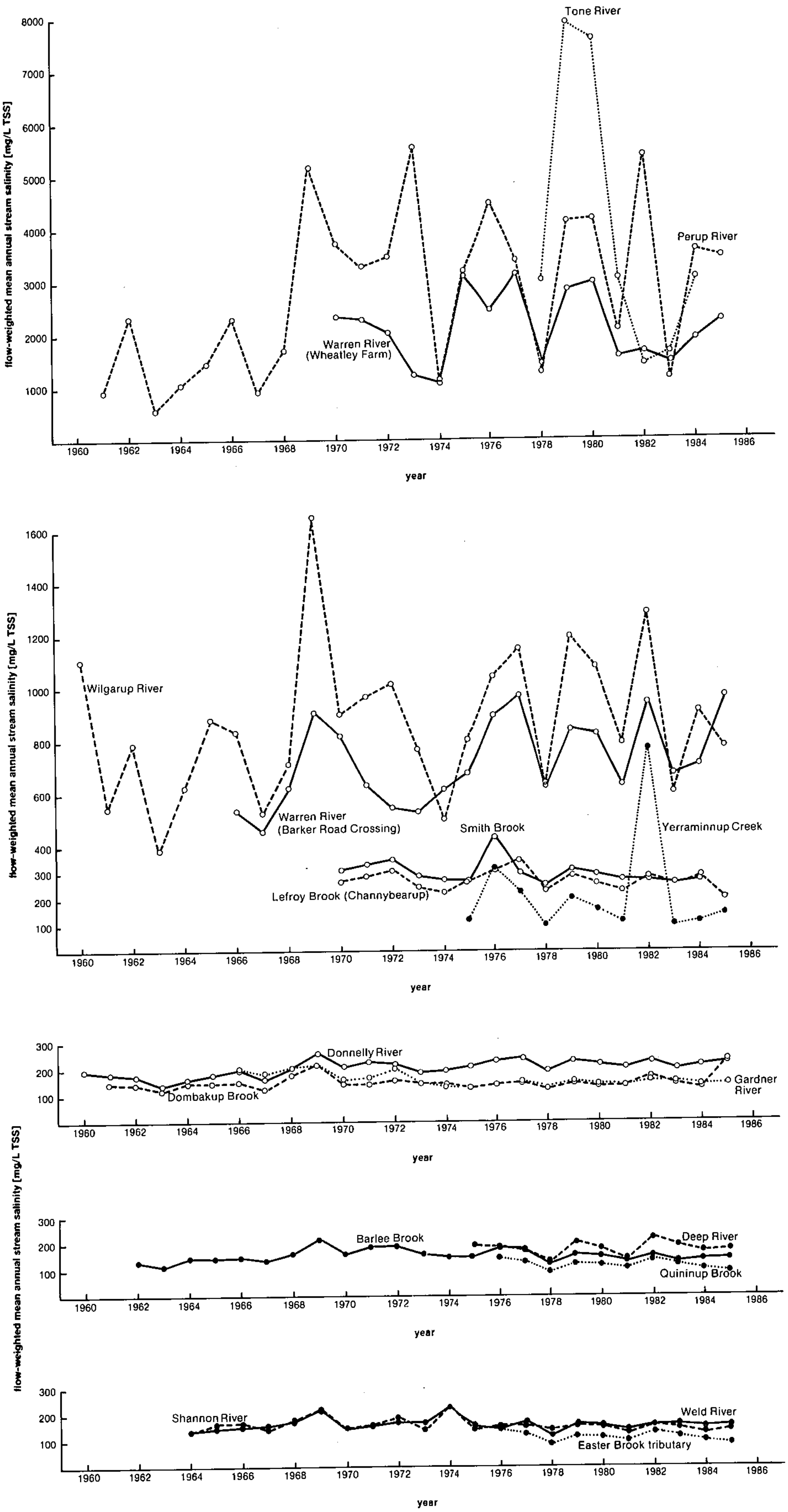


Figure 5

Flow-weighted mean annual salinity of several streams in the research area from 1960 to 1985. (Data from the Conrec data base of the Water Authority of Western Australia, and Public Works Department of Western Australia 1984. Closed circles are for streams without significant agricultural development in their catchments. Open circles are for streams with significant agricultural development in their catchments. Different line types were chosen for clarity.)

landscape position cannot be ascertained since logging in the catchments of the larger streams commenced several decades before stream salinities were monitored. As a result of local geologic, climatic and hydrologic characteristics small streams can have salinities similar to those of larger streams (see Yerraminnup Creek) or sometimes even higher salinities (see Iffley catchment in section 5.4).

The re-introduction of heavy selection cutting had no notable effect on the salinity of the Weld and Shannon Rivers (Fig. 5). Barlee Brook was not affected either, but since the change in cutting strategy there was also little logging in its catchments until 1986. The records for all other streams in Table 3 are too short to make such a comparison. In the Weld River, Shannon River and Barlee Brook catchments, the mean annual rainfall is well above 1100 mm. The effect on stream salinity of disturbance to the native vegetation generally increases with decreasing mean annual rainfall (Collins and Barrett 1980). The observation that the change in cutting strategy did not affect stream salinity in these three catchments should therefore not be extrapolated to areas of lower mean annual rainfall.

Clearing for agriculture in areas with more than 1100 mm mean annual rainfall had little effect on stream salinity (Table 3). However, as the mean annual rainfall decreases agricultural development is associated with increasingly higher flow-weighted mean annual stream salinities. Variations from year to year and within a year become greater too. It can take several decades for agricultural clearing to reach its full impact on stream salinity (Hookey 1987). Hence, stream salinity in catchments with agricultural development often shows a rising trend as demonstrated by the Wilgarup and Warren Rivers in Figure 5. In areas with less than 900 mm mean annual rainfall the flow-weighted mean annual stream salinity can frequently exceed 2000 mg/L TSS. Year to year variations of several thousand mg/L TSS are not uncommon, and within a year stream salinity can range from a few hundred to over 10 000 mg/L TSS. If no steps are taken to restore the salt and water balance to the state prior to clearing it will take several hundred years for such streams to yield high quality drinking water again (Peck and Hurle 1973; Hookey 1987).

Saline flows from agricultural areas are often diluted as they move through forest. This is exemplified by the Warren River. Most of its salinity arises in agricultural areas drained by the Tone and Perup River. At Wheatley Farm, some 20 km downstream of the confluence of those two tributaries, the flow-weighted mean annual salinity of the Warren River is over 2000 mg/L TSS. At Barker Road crossing, after flowing through mostly forest for some 75 km, it has decreased to less than 1000 mg/L TSS. To a lesser degree this dilution effect also occurs in the Lefroy Brook between the Channybearup and Rainbow Trail gauging stations.

Further details about stream water quality in the Shannon, Warren and Donnelly River basins are given elsewhere (Collins and Barrett 1980; Steering Committee 1980).

3. HYDROLOGY OF THE RESEARCH AREA

3.1 Hydrologic characteristics of mature forest areas

Hydrologic processes are strongly influenced by rainfall. This report therefore differentiates between three rainfall zones which are defined as:

high rainfall zone = areas where the mean annual rainfall is greater than 1100 mm;

intermediate rainfall zone = areas where the mean annual rainfall is between 1100 mm and 900 mm;

low rainfall zone = areas where the mean annual rainfall is less than 900 mm.

All statements in this chapter refer to the southern forest although some of the information presented was actually obtained in catchments of similar hydrology in the jarrah forest of the Darling Range to the north.

The soils in the southern forest typically consist of 30 to 100 cm of sandy to loamy material on top of 5 to 20 m of clay-rich material (McArthur and Clifton 1975). The latter ranges in texture from sandy clay loam to clay but is hereafter simply referred to as clay. The upper soil is very permeable so that surface runoff is hardly ever generated because the rainfall rate exceeds the infiltration capacity of the upper soil. The permeability of the underlying clay, however, is very low and water is frequently perched above it during the wet season. Part of this water eventually infiltrates into the clay to recharge soil moisture and ground water, and part of it is removed by evapotranspiration. The remainder flows downslope on top of the clay layer and discharges into streams. Such shallow subsurface runoff is likely to contribute over 90 per cent of the annual streamflow volume (Stokes and Loh 1982).

After a large amount of rain has fallen enough water may be perched to completely saturate the soil above the clay horizon. Any additional rainfall may then become surface runoff. In winter complete soil saturation occurs frequently in valleys since they receive water from rainfall as well as shallow subsurface flow originating upslope. Nevertheless, surface runoff apparently provides less than 5 per cent of the annual streamflow volume (Stokes 1985).

Depth to ground water is related to mean annual rainfall and fluctuates seasonally in response to the succession of water excess in winter and water deficit in summer. Throughout this report ground water is classified as subsurface water which occurs in saturated soil and rock formations. Subsurface water held in unsaturated soil and rock formations is referred to as soil water. Following these definitions water retained in saturated soil above the clay horizon would count as ground water, but shall be called perched water instead because it generally occurs intermittently and only in winter.

In the high rainfall zone ground water is generally quite close to the soil surface, especially in the valleys, and during winter the large water excess commonly leads to enough recharge to raise ground water above the water level in the streams so that it contributes to streamflow. In the low rainfall zone ground water is typically well below the soil surface and the smaller water excess usually far from sufficient to lead to any ground water discharge to streams. In the intermediate rainfall zone the situation depends largely on local conditions. Some areas discharge ground water to streams in most winters, others occassionally or never. Ground water may contribute around 10 per cent of the annual streamflow volume in the high rainfall zone (Stokes and Loh 1982), but this percentage decreases to nil in the low rainfall zone. Recent data by Stokes (1985) suggest that even in the high rainfall zone ground water contributes far less than 10 per cent of the annual streamflow volume.

As a consequence of the water deficit, soil water is depleted by evapotranspiration during the summer. This creates an upward hydraulic gradient which causes water to flow from the saturated zone towards the top of the unsaturated zone where it is then removed by evapotranspiration. Some water in the saturated zone may also be extracted directly by deeply rooted plants. Which pathway is more important depends on the depth to ground water, the hydraulic properties of the soil, the depth to which roots penetrate and physiological properties of the vegetation at the site. Lateral ground water flow may also remove some water, but the amount appears to be smaller than that consumed by evapotranspiration (Sharma et al. 1982). These processes lead to a sufficient decline in ground water level during summer to stop ground water discharge to streams in most areas. Because of the dry conditions there is also hardly any surface or subsurface runoff during summer. About 90 per cent of the annual streamflow volume is therefore generated from May through October (Fig. 6) when most of the rainfall occurs and the soils are wet. Small streams usually stop flowing in summer.

Water which enters a catchment as rainfall (R) may leave it as streamflow (Q), evaporation (E) or transpiration (T) or add to soil and ground water storage (WS). This water balance can be summarised as

$$\Delta WS = R - Q - E - T$$

There may also be some ground water outflow from a catchment, but in the research area this is generally less than one per cent of the annual rainfall (Steering Committee 1980) and is therefore not considered.

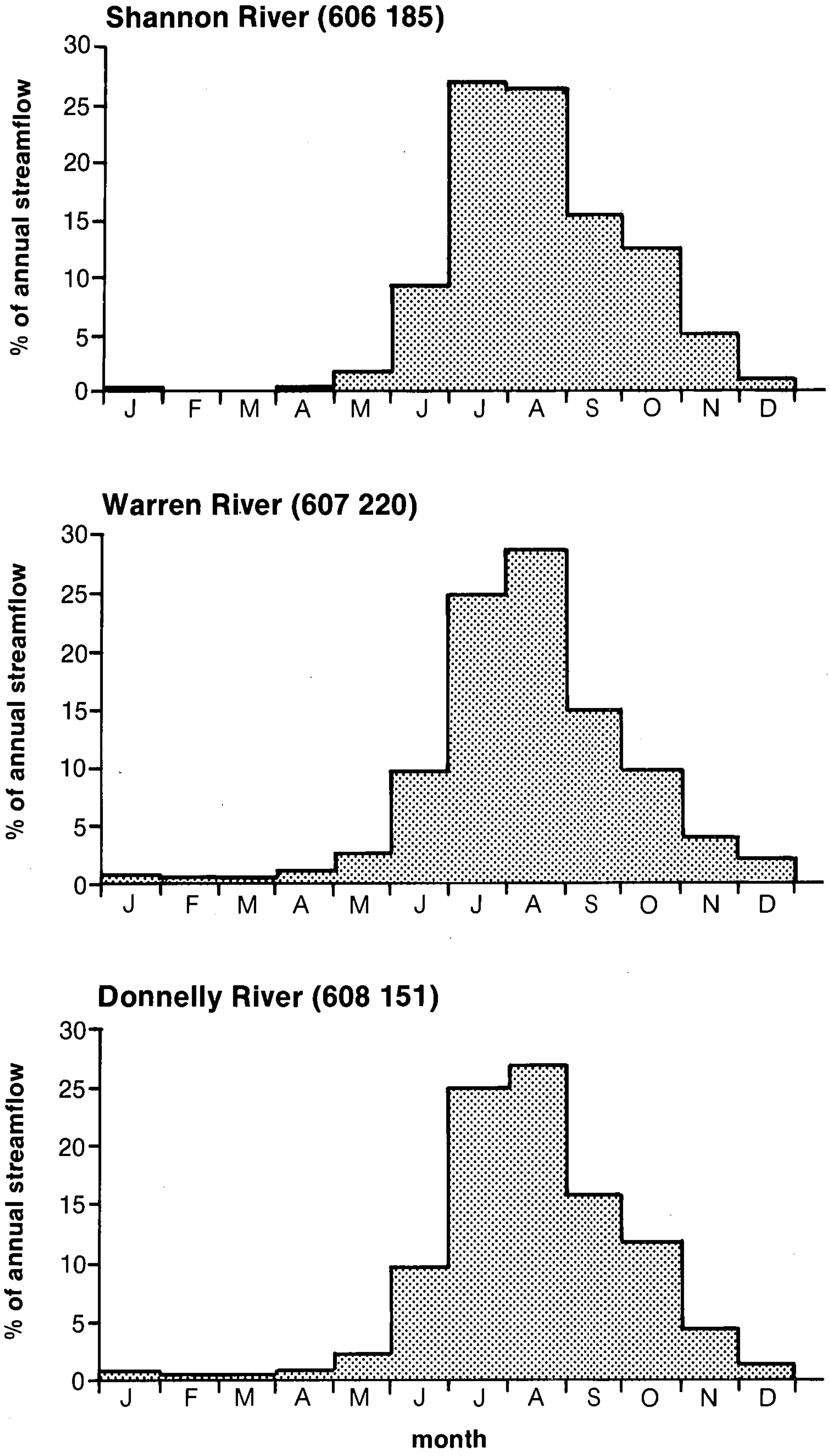


Figure 6

Average monthly distribution of annual streamflow for three major streams in the research area. (Data from Collins and Barrett 1980. The numbers in parentheses are the gauging station numbers.)

The symbol Δ stands for 'change in'. Soil and ground water depletion during summer is generally about equal to the replenishment during winter so that there is no significant change in water storage from one year to the next (Sharma et al. 1982). Streamflow typically exports 10 to 20 per cent of the annual precipitation in the high rainfall zone, but less than 5 per cent in the low rainfall zone where small streams often do not flow at all in years of below average precipitation.

Transpiration is defined here as the loss of water from within living plants to the atmosphere. All other water loss to the atmosphere is called evaporation. The magnitude of evaporation and transpiration in the southern forest has not been evaluated separately. However, evapotranspiration, the combination of both processes, ranges from 80 to 90 per cent of the annual precipitation in the high rainfall zone to 95 to 100 per cent in the low rainfall zone (Fig. 7).

Because of the different mechanisms involved in water uptake by plant roots and water movement in soil, more water can usually be lost from a unit area of soil covered by vegetation than from a unit area of bare soil (Hillel 1982). However, similar amounts may be lost if the soil surface is wet. Vegetation typically covers 70 to 90 per cent of the soil surface in forested areas (Stoneman et al. 1987), and only during winter when potential evapotranspiration is low is the soil surface frequently wet. Evaporation from the soil is therefore probably less than 10 per cent of the total annual rainfall. In this report dead organic litter on the forest floor is considered to be a part of the soil surface. Rainfall intercepted by vegetation is subsequently lost to the atmosphere. This form of evaporation, generally called interception, is likely to consume 10 to 20 per cent of the total annual rainfall (Schofield et al. 1987). Transpiration therefore probably accounts for 60 to 70 per cent of the total annual rainfall in the high rainfall zone, and 80 to 90 in the low rainfall zone.

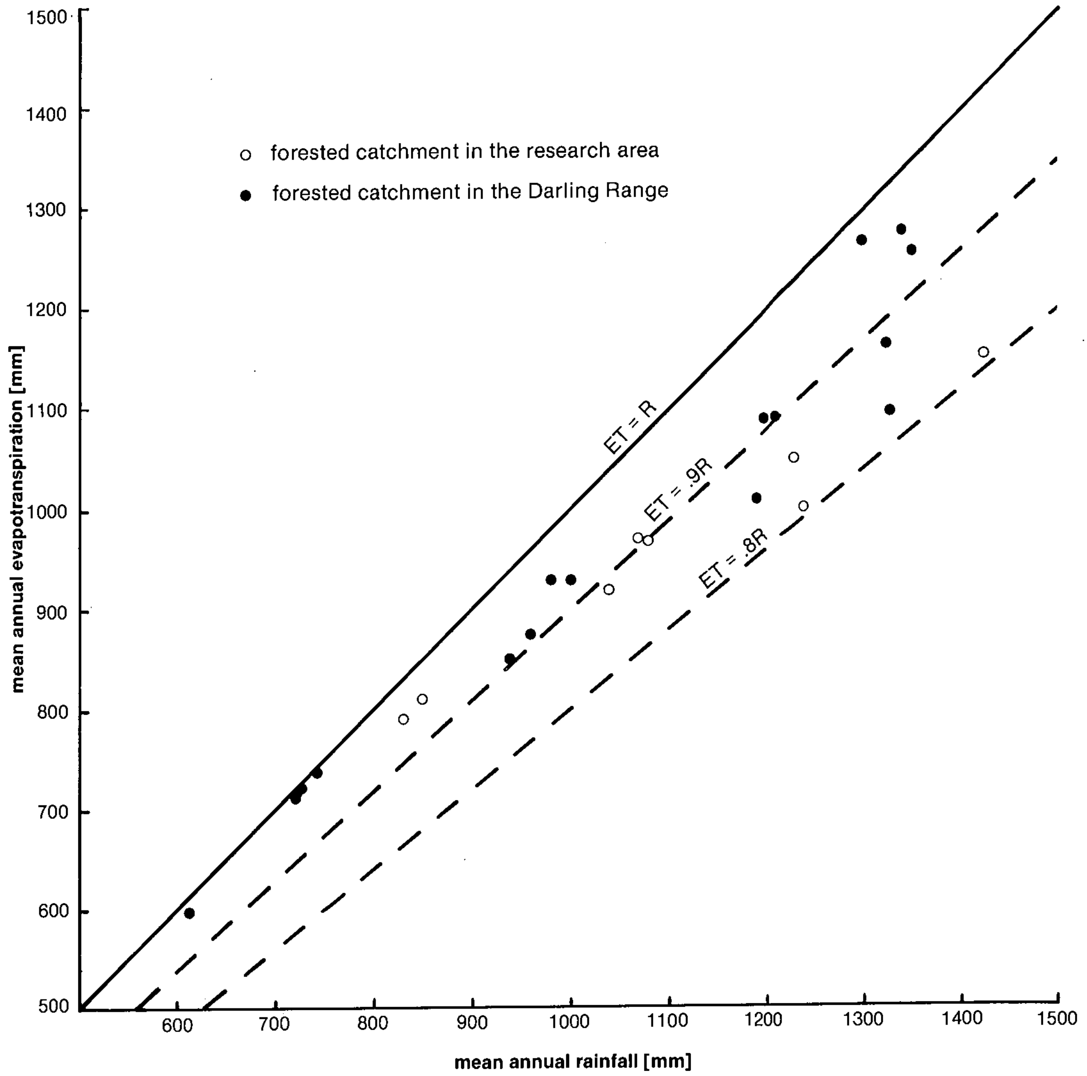


Figure 7

Mean annual evapotranspiration (ET) in relation to mean annual rainfall (R) in forested catchments in south-west Western Australia. (Based on Loh 1982. Annual evapotranspiration was estimated as annual rainfall minus annual streamflow.)

In south-west Western Australia rain and dry fallout precipitate salt which was transferred into the atmosphere from oceanic spray (Hingston and Gailitis 1976). The amount precipitated decreases with distance from the coast (Fig. 8). Dividing the total annual saltfall by the annual rainfall yields an effective salt concentration of rainwater. This value is about 35 mg/L TSS near the coast, but decreases rapidly with distance from the coast (Fig. 8).

Evapotranspiration removes most of the water but leaves all salt behind. Due to this concentration process surface and shallow subsurface runoff, ground water, and hence streams have higher salinities than rainwater. Salt left on the soil surface is eventually washed into the profile by rainfall, or carried to a stream by surface runoff. Shallow subsurface runoff moves most of the salt from the soil above the clay horizon to a stream, but some is also transported into the clay by infiltrating water. Ground water can discharge salts from deeper parts of the soil profile directly to the streams. However, water flowing from the saturated zone to the soil surface, as typically encountered in summer, also carries salt into the soil above the clay horizon and to the soil surface where it may subsequently be removed by runoff. This could be considered as indirect discharge of salt to streams by ground water. It seems that ground water discharges more salt via the indirect than the direct pathway (Stokes 1985).

These processes leach most of the salt from the top 1 to 3 m of a soil profile. Solute contents in this zone are therefore generally well below 0.1 kg/m^3. However, at greater depths leaching is less complete and substantial amounts of salt have accumulated. More than 3 kg/m^3 TSS are not uncommon, especially in the low rainfall zone. On hilltops and upper slopes the salt content typically increases monotonically with depth. On middle and lower slopes and in valleys it typically increases to a maximum at an intermediate depth and then decreases again. This pattern is commonly referred to

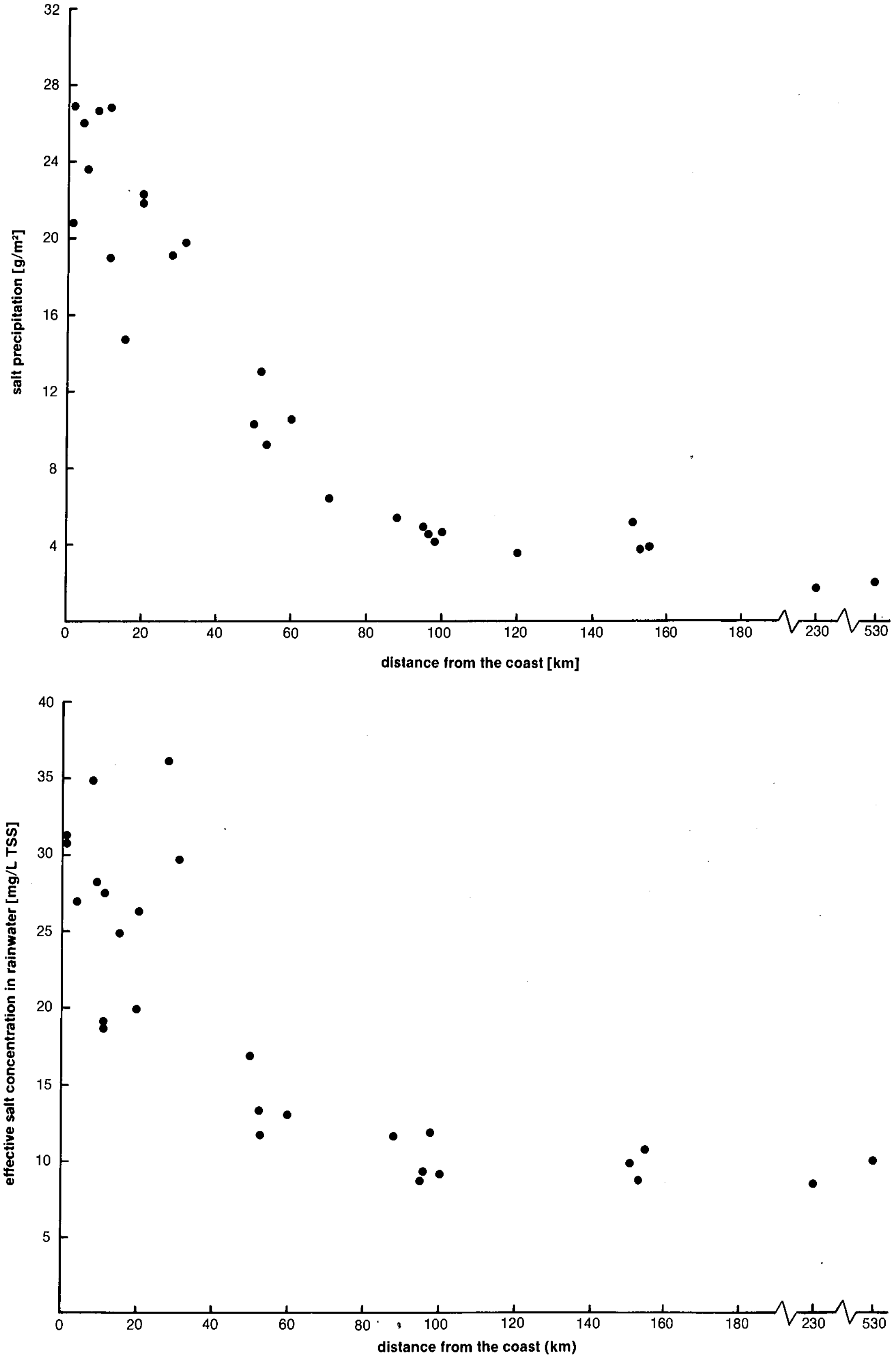


Figure 8

The amount of salt precipitated by rainfall and dry fallout and the effective salt concentration in rainwater in south-west Western Australia in relation to distance from the coast. (Based on Hingston and Gailitis 1975, 1976.)

as a salt bulge (Fig. 9). Salt bulges usually occur above the saturated zone. While the causes for the different salt distributions are not completely understood, it appears that salt contents monotonically increasing with depth are usually associated with net ground water recharge, while salt bulges are mainly connected with net ground water discharge (Johnston 1981).

Salt is still accumulating. In the high rainfall zone probably less than 10 per cent of the salt introduced to a catchment each year by rainfall and dry fallout is retained. However, there are some catchments in the high rainfall zone and even some in the intermediate rainfall zone which have a net salt discharge. These tend to be in areas where forest density has been significantly reduced by past logging or jarrah dieback (Schofield _et_ _al_. 1987). In the low rainfall zone more than 50 per cent of the total annual saltfall is typically retained. The portion retained also varies between catchments of similar rainfall and years (Steering Committee 1980; Stokes 1985).

Soil salt storage in the research area currently ranges from less than 5 kg/m^2 TSS to nearly 65 kg/m^2 TSS. It varies greatly between sites within catchments and between catchments of similar rainfall, but generally increases with decreasing mean annual rainfall (Fig. 10). The values tend to be higher in valleys and on lower slopes which are usually ground water discharge areas. Comparing these values with the saltfall data in Figure 8 suggests that it took several thousand years to accumulate the present amounts of salt in the soils. Further information on soil salinity in the area is provided by Johnston _et_ _al_. (1980).

Due to a variety of processes involved in the release of salt from the soil matrix, low flows remove more salt per unit quantity of water than high flows (Rhoades 1974). In general the salinity of surface and shallow subsurface runoff is therefore inversely related to runoff volume. Because of the low salt content in the upper soil, it is usually well below

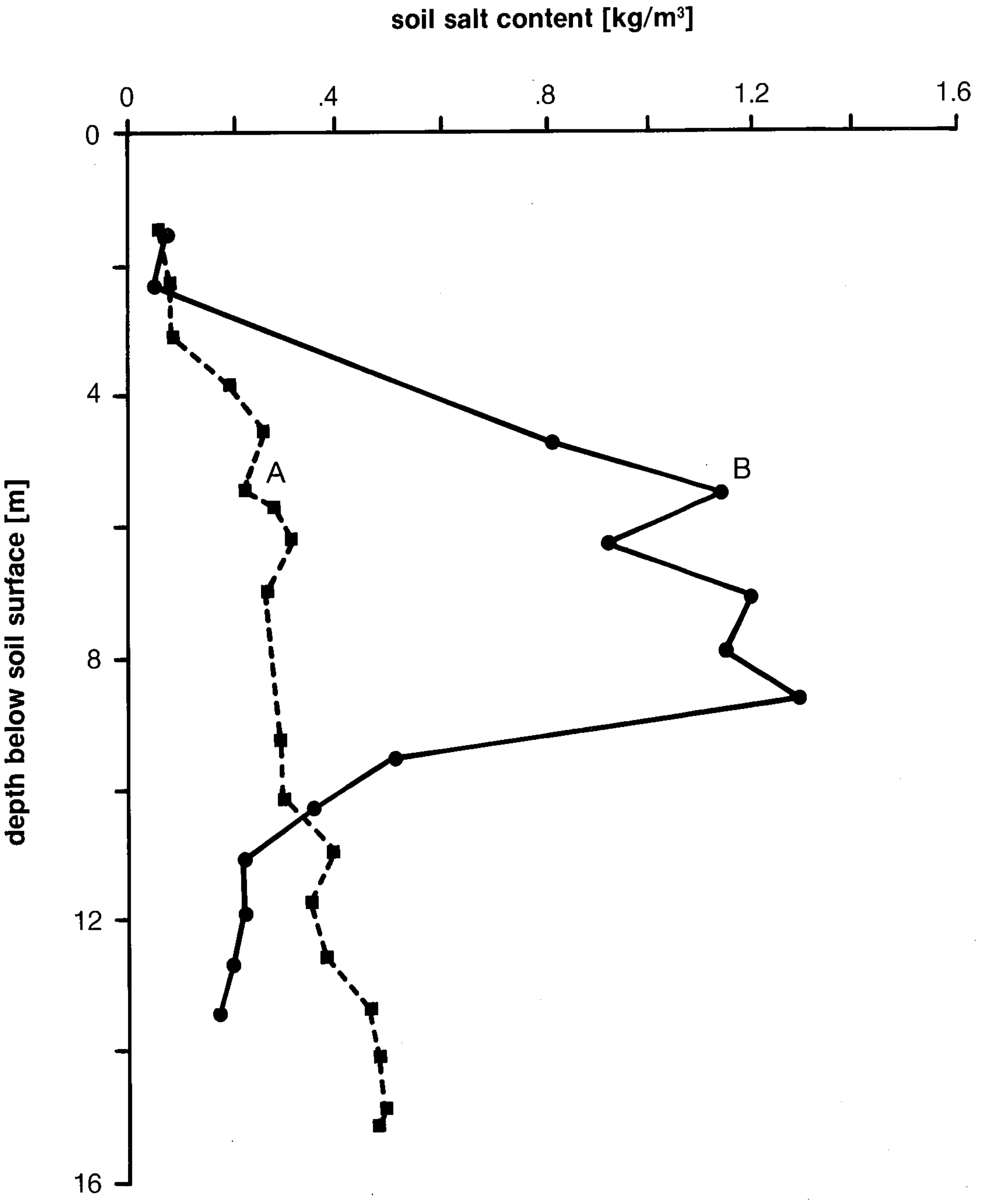


Figure 9

Two typical patterns of salt distribution in soils in the research area:
A. salt content increasing monotonically with depth (bore number 6078610);
B. salt bulge (bore number 6078617).
(Data from Johnston et al. 1980.)

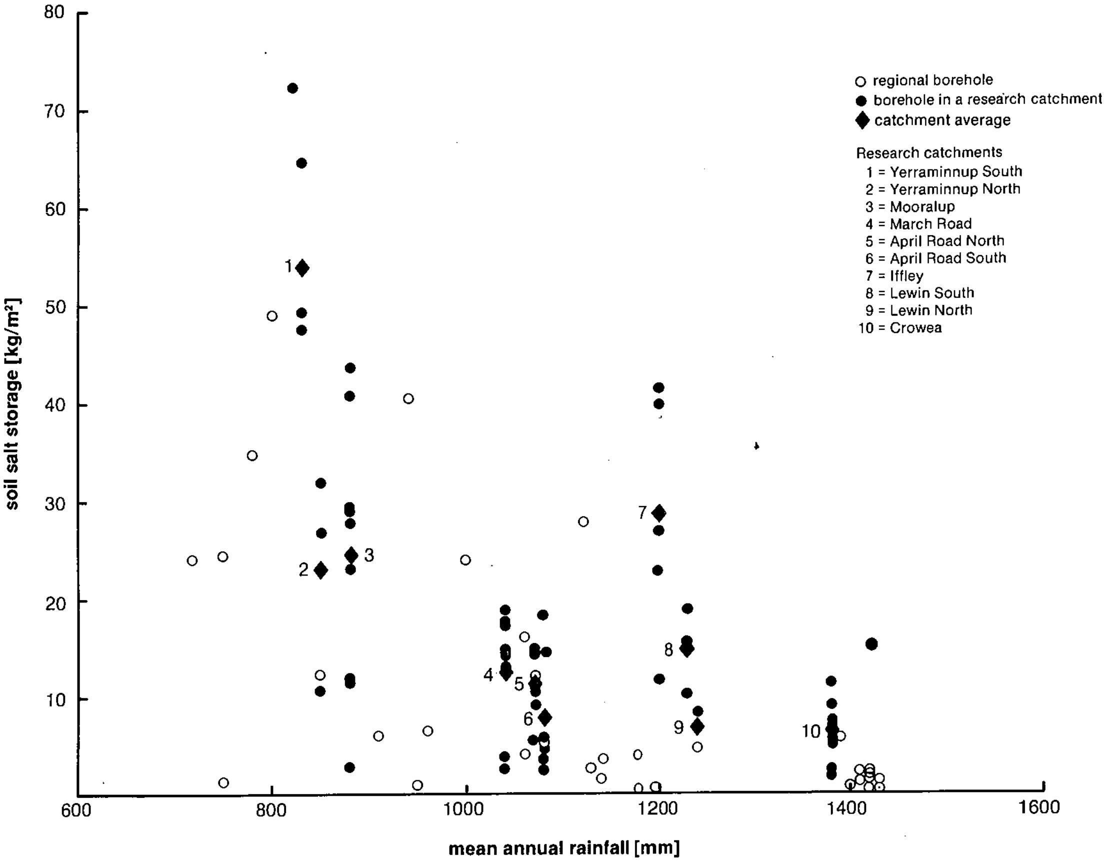


Figure 10

Soil salt storage in relation to mean annual rainfall at several bore locations in the research area. (Data from Johnston et al. 1980. Crowea, Iffley and Mooralup are research catchments discussed in detail in this study. The other seven catchments are discussed in detail by Borg et al. 1987.)

500 mg/L TSS, and frequently even less than 100 mg/L TSS (Sharma et al. 1980; Stokes 1985). Ground water salinity is generally less than 1000 mg/L TSS in the high rainfall zone, but values above 10 000 mg/L TSS are common in the low rainfall zone (Steering Committee 1980), reflecting the increase in salt storage with decreasing mean annual rainfall. Because it has a higher salinity than surface and shallow subsurface runoff, even a small amount of ground water can have a large influence on stream salinity. This is illustrated by data from the Wights catchment near Collie, some 100 km north of Manjimup. Stokes and Loh (1982) calculated that 60 per cent of the salt but only 7 per cent of the water in its 1980 streamflow came from ground water discharge. Shallow subsurface runoff contributed 38 per cent of the salt, but 91 per cent of the water. Just 2 per cent of the salt and 2 per cent of the water were associated with surface runoff.

3.2 Hydrologic processes affected by logging

Logging removes vegetation and therefore reduces transpiration and interception in cut-over areas. More water thus becomes available for other parts of the water balance. Some of it goes into storage which leads to a rise of the ground water level. Hence, where ground water already contributed to streamflow prior to logging, more ground water, and with it more salt, will be discharged to the streams. In areas where ground water did not contribute to streamflow prior to logging, the rise in ground water level after logging may be sufficient in some cases to result in ground water and associated salt discharge to streams. A rise in ground water level is also likely to lead to an increase in the indirect discharge of salt by ground water since flow from the saturated zone towards the soil surface generally increases the closer the ground water level is to the soil surface (Hillel 1982).

Due to the increase in water storage, the soil profile is generally wetter after logging than before. More of the soil surface is exposed to the atmosphere, too. Both factors are responsible for an increase in evaporation, but total evapotranspiration is still less than prior to logging. The wetter soil conditions also generate more shallow subsurface and surface runoff and thus more streamflow since less rainfall is now required to perch water above the clay horizon or saturate the surface soil. The effect of a rise in ground water level on stream salinity therefore depends on how much increased runoff dilutes the additional salt discharge by ground water.

Prior to this research there was no quantitative information on how heavy selection cutting or clear-felling would influence streamflow and stream salinity in the southern forest of Western Australia, or how long any effect might persist after regeneration. This was the general question addressed in this study.

Of particular interest was the situation in the low rainfall zone in the north-east sector of the research area where clearing for agriculture had caused large and persistent increases in stream salinity. This raised some concern that heavy selection cutting might lead to a serious stream salinity problem, too (Forests Department of Western Australia 1973). Logging in the north-east sector was therefore restricted to the selective removal of sawlogs until research could show that heavy logging was possible without causing significant increases in stream salinity. Two experimental catchments, one in this study and one in the paired catchment study mentioned in the introduction, were logged intensively to examine the effect of stream salinity.

In the high rainfall zone agricultural development had little effect on stream salinity, and in the intermediate rainfall zone the effect was moderate (Table 3). Furthermore, heavy selection cutting or clear-felling followed by regeneration of the cut-over area to forest is a less severe hydrologic disturbance than clearing for agriculture. Hence, no serious stream salinity increase was expected in these rainfall zones and the change from light selection cutting to heavy selection cutting and clear-felling was permitted without waiting for the research results.

4. INSTRUMENTATION AND MEASUREMENTS

Four small catchments were selected in 1975 to represent a combination of mean annual rainfall, forest type, soils and topography found in the southern forest. Their names and some of their characteristics are given in Table 4 and their locations are shown in Figures 1 and 2. Catchment maps are presented in Appendix J. The catchments are of similar size to areas cut in commercial logging operations.

All catchments were instrumented in a similar fashion during 1975. Four storage rain-gauges, each 127 mm in diameter, were located in the Poole catchment and six in or near each of the other three catchments. They were placed where substantial gaps occurred in the tree canopy. Their location is indicated on the maps in the Appendix J. Tall overstorey vegetation which could have influenced the amount of rainfall collected was cleared from near the gauges. The gauges were read at least once a week and the values for each group of gauges averaged to get a mean rainfall for the catchment. These means were then summed to obtain the total annual rainfall.

At the outlet of every catchment a weir was constructed with a stilling basin behind it. Figure 11 gives a schematic of such an installation. In 1976 the water level in each stilling basin was determined once every two or three days using a staff gauge. With the procedure described below, this frequency of measurement appears sufficient to estimate the total annual streamflow volume in small catchments within 5 per cent of the volume obtained from a continuous water level record (Herbert and Ritson 1976). Since 1977 a floatwell installed in each stilling basin and connected to a chart recorder supplied a continuous record of the water level. An equation relating the water level in the stilling basin to flow over the weir was used to compute streamflow rates (U.S. Dept. of the Interior 1971). The streamflow rates for 1976 were then multiplied by the time between measurements and summed to get the total

Table 4: Some characteristics of the four small catchments selected for this study.

Catchment	Location	Size [ha]	Annual rainfall [mm] long-term mean[1]	Annual rainfall [mm] mean for 1976 through 1985	Mean annual pan evaporation[2] [mm]	Forest type	Soils
Crowea	116° 6' 18" E 34° 32' 54" S	114	1 380	1 101	1 210	karri (99 ha) jarrah (15 ha)	red and yellow duplex soils
Poole	116° 13' 18" E 34° 34' 12" S	121	1 310	1 069	1 240	karri (91 ha) jarrah (30 ha)	mostly yellow duplex soils, some laterite and colluvium
Iffley	115° 46' 42" E 34° 16' 54" S	175	1 200	861	1 150	jarrah (175 ha)	various kinds of duplex soils, some gravelly loam associated with laterite
Mooralup	116° 20' 36" E 34° 19' 24" S	112	880	698	1 350	jarrah (112 ha)	red and yellow duplex soils, some colluvium and sand

[1] estimated from Figure 2

[2] estimated from Figure 3

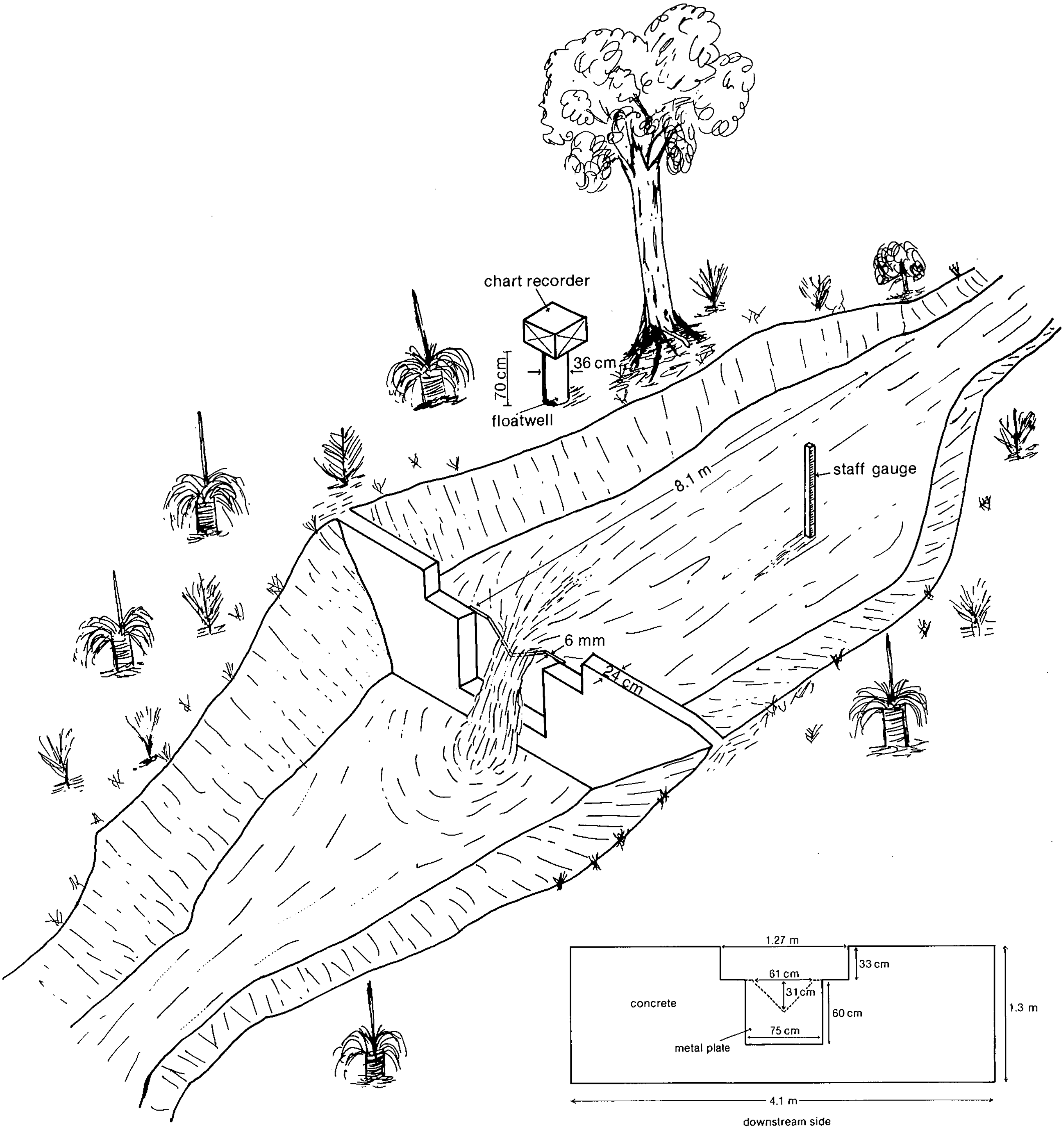


Figure 11

Schematic of the type of gauging station constructed in the four research catchments. (Indicated dimensions apply to the gauging station at Iffley but are similar for the gauging stations at Crowea, Poole and Mooralup.)

annual streamflow volume. The streamflow rates for all subsequent years were integrated numerically over time to obtain the total annual flow volume.

Once a week a 250 mL sample was taken from the top 10 cm of water in each stilling basin. The water samples were taken to the laboratory to measure their electrical conductivity. The temperature of each sample was determined shortly before the conductivity measurements were taken. The readings from the conductivity meter could thus be converted to equivalent electrical conductivities at 25°C using a conversion table. These values were then employed to calculate the concentration of total soluble salts (TSS) in the sample from a regression equation by Hatch (1976). Finally, a flow-weighted mean annual stream salinity, S, was computed as

$$S = \frac{\Sigma S_i \; Q_i}{\Sigma Q_i}$$

where Q_i is the streamflow volume on the day when the water sample with the TSS concentration S_i was collected.

Ten 127 mm diameter holes were auger-drilled to bedrock in every catchment to monitor ground water levels. They were positioned to represent valley, midslope and upslope areas. Two additional holes were located outside each catchment in forested areas which were not to be logged. All bores were drilled and constructed by the Mines Department of Western Australia and given a seven digit Australian Water Resources Council identification number. However, for simplicity they are referred to as bore number 1 through 48 in this report (Appendix H). A 38 mm diameter PVC pipe, fitted to reach from the bottom of the hole to 50 cm above the soil surface, was inserted into each hole and packed into place with graded sand. Each pipe was slotted from 150 cm below the soil surface to the bottom of the hole, and its bottom end sealed with a plug. For protection, an 89 mm diameter steel pipe was placed over all PVC pipes. The steel pipes extend 50 cm above and

100 cm below the soil surface and are cemented in at the soil surface. In a few bores the water level rose beyond 50 cm above the soil surface after logging. The height of the steel pipe in these bores was increased to accommodate the high water levels. Removable caps were placed on top of all steel pipes to prevent rain and debris from entering the bores. Bore construction details are illustrated in Figure 12. The location of the bores is marked on the maps in Appendix J.

The water level in every bore was determined once a month using a tape measure with a small bailer attached to it. When lowered down the PVC pipe the bailer makes a distinct sound when it contacts the water surface. The depth to water is then read off the tape measure and corrected for the height of the pipe above the soil surface. After that the bailer was lowered a few centimetres below the water surface to collect a 100 mL sample. The TSS concentration of this water sample was later determined in the laboratory in the manner described above.

Rainfall, streamflow and stream salinity was monitored from the beginning of 1976 to the end of 1985. The collection of bore water level data commenced in May 1975 and is still going on. The collection of bore water salinity data also began in May 1975, but was stopped in June 1986.

All four catchments were logged as part of commercial logging operations. Due to management constraints the areas logged therefore do not entirely match the actual catchment areas (see Appendix J). At Crowea 108 ha of karri forest were clear-felled and some 25 ha of jarrah forest logged using heavy selection cutting to an estimated average basal area (over bark at breast height) retention of 11 m^2/ha. Most of the logging took place from January 1977 until the end of July 1977. However, some 10 ha of karri forest next to the stream and the jarrah stand were not cut until the following summer. Logging was completed in February 1978. At Poole 218 ha of karri forest were clear-felled and 38 ha of jarrah forest logged

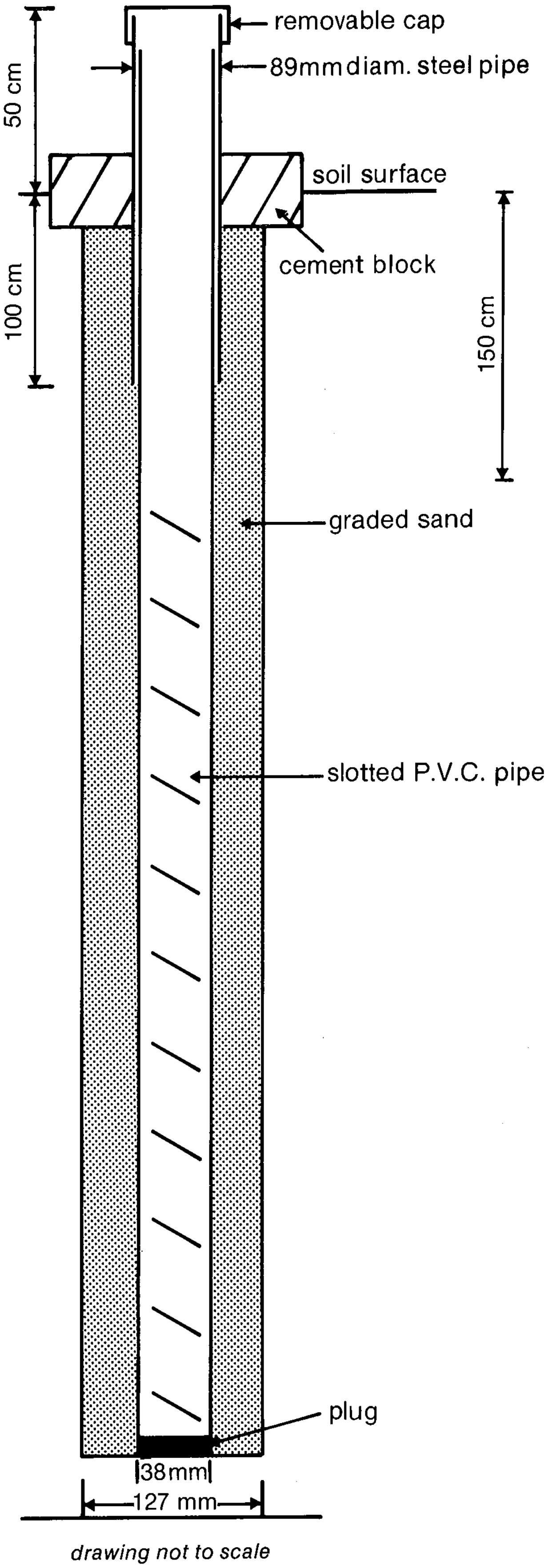


Figure 12
Schematic of the type of bore constructed in the four research catchments.

under heavy selection cutting to an estimated basal area retention of 11 m^2/ha. The karri forest at Poole contained a substantial amount of jarrah. The bulk of the area was logged from January 1977 to the end of August 1977. The remainder, some 30 ha of karri forest adjacent to the stream and the jarrah area, were cut during the next summer. Logging was completed in March 1978. All cut-over areas at Crowea and Poole were burnt in April 1978 to dispose of the waste from logging. The karri areas were then regenerated by hand-planting nursery-raised karri seedlings in a 2 m by 4 m spacing. The jarrah areas were left to regenerate naturally.

At Iffley a total of 146 ha of jarrah forest were logged under heavy selection cutting to a measured average basal area retention of 11.4 m^2/ha, which corresponds to 15.1 per cent overstorey cover. Logging began in November 1976 and proceeded to the end of May 1977. About 106 ha were cut in this period. The other 40 ha which were adjacent to the main stream were cut during the summer of 1977-78. Logging was finished in February 1978. At Mooralup some 166 ha of jarrah forest were logged under heavy selection cutting to a measured average basal area retention of 10.6 m^2/ha, which corresponds to 14.2 per cent overstorey cover. Logging commenced in December 1976 and was completed by the end of May 1977. Waste disposal burns in the cut-over areas at Iffley and Mooralup were carried out in November 1979. They were then left to regenerate naturally. Table 5 summarises logging and regeneration details for all four catchments.

Table 5: Summary of logging and regeneration details for the four research catchments.

catchment	logging period	logging method	area logged [ha]			wood volume extracted [m^3]			regeneration
				total	within catchment		total	within catchment	
Crowea	January 1977 through February 1978	karri areas: clear-felling jarrah areas: heavy selection cutting with an average of $\sim$11 m^2/ha basal area retention	karri: jarrah:	108 25	95 15	karri sawlogs: jarrah sawlogs: karri chipwood: marri chipwood:	13 200 980 2 500 18 700	11 600 590 2 200 15 500	karri areas: burnt in April 1978, then hand-planted in a 2 m by 4 m spacing with nursery-raised karri seedlings. jarrah areas: burnt in April 1978, followed by natural regeneration.
Poole	January 1977 through March 1978	karri areas: clear-felling jarrah areas: heavy selection cutting with an average of $\sim$11 m^2/ha basal area retention	karri: jarrah:	218 38	90 30	karri sawlogs: jarrah sawlogs[1]: karri chipwood: marri chipwood:	24 400 7 780 7 720 20 000	10 100 3 650 3 190 9 380	karri areas: burnt in April 1978, then hand-planted in a 2 m by 4 m spacing with nursery-raised karri seedlings. jarrah areas: burnt in April 1978, followed by natural regeneration.
Iffley	November 1976 through February 1978	heavy selection cutting with 11.4 m^2/ha basal area retention		146	127	jarrah sawlogs: marri chipwood:	6 180 12 800	5 380 11 100	burnt in November 1979, followed by natural regeneration.
Mooralup	December 1976 through May 1977	heavy selection cutting with an average 10.6 m^2/ha basal area retention		166	96	jarrah sawlogs: marri chipwood:	5 790 12 700	3 350 7 350	burnt in November 1979, followed by natural regeneration.

[1] karri stands in this catchment contained substantial amounts of jarrah and supplied about 80% of the jarrah sawlogs

5. RESULTS

5.1 General remarks

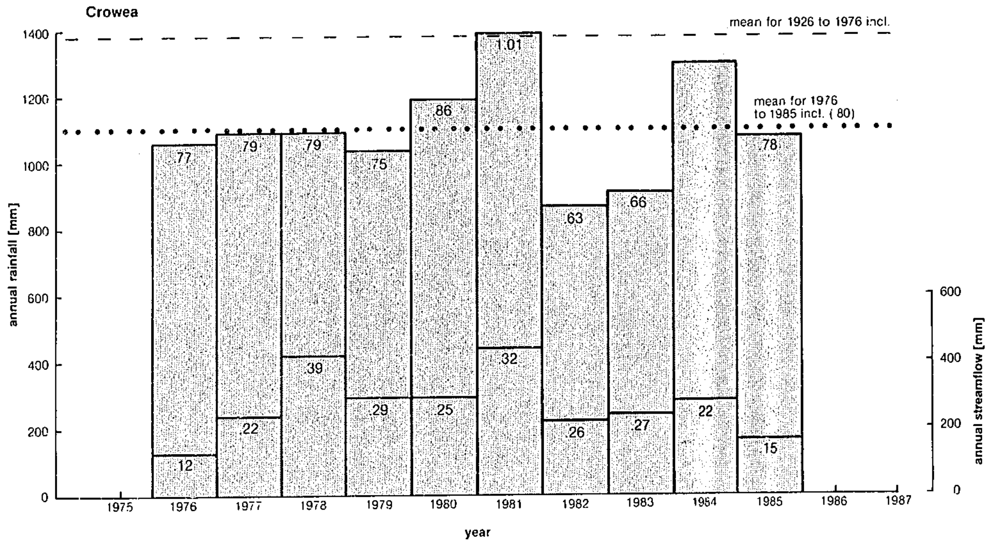
A graphical summary of the annual values of rainfall, streamflow, stream salinity, minimum bore water level and vegetation cover in the four catchments during the study period is shown in Figure 13. The numbers on top of the rainfall bars state the ratio between the rainfall in the respective year and the mean annual rainfall for 1926 to 1976 inclusive. Streamflow data are presented as annual streamflow volumes per unit catchment area and are expressed in units of millimetres to allow direct comparisons with annual rainfall. Streamflow bars are plotted inside the rainfall bars and at the same scale. The numbers at the top of the streamflow bars give the annual streamflow as a fraction of the rainfall in the respective year. All stream salinities are flow-weighted mean annual values.

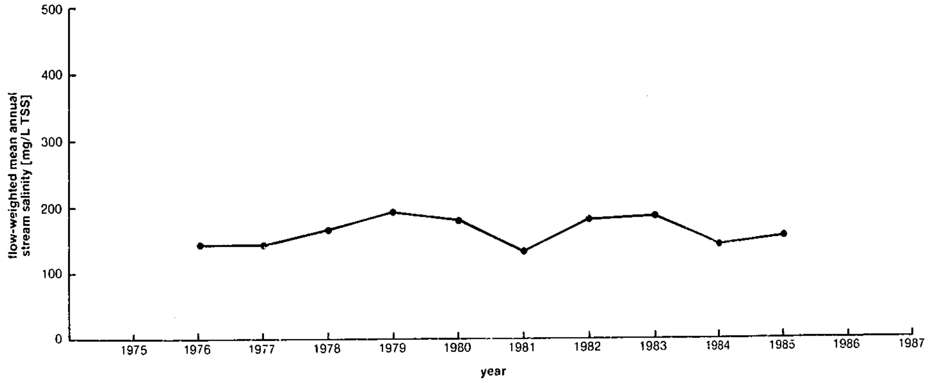
Ground water status in a given year is represented by the average of the yearly minimum water level of all bores in a catchment, relative to the 1976 value. The bores did not become operational until May 1975 when some were already past their minimum water level. This should be considered when referring to the 1975 bore water level data.

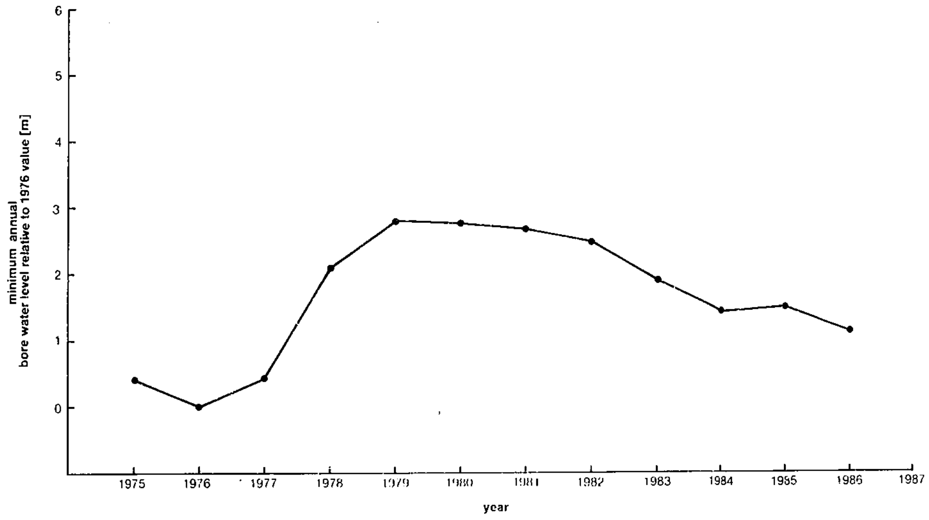
The vegetation cover data for 1986 were obtained in the catchments. Clear-felling and the subsequent controlled burn reduced vegetation cover briefly to zero at Crowea and Poole in 1978. Basal area was measured at Iffley and Mooralup in 1978-79 and converted to overstorey cover using a correlation between basal area and overstorey cover based on data from Stoneman _et_ _al_. (1987). The waste disposal burn in 1979 temporarily reduced the understorey cover to zero in both catchments so that overstorey and total vegetation cover were equal for a short time. All other cover data were inferred from the information given in section 6.

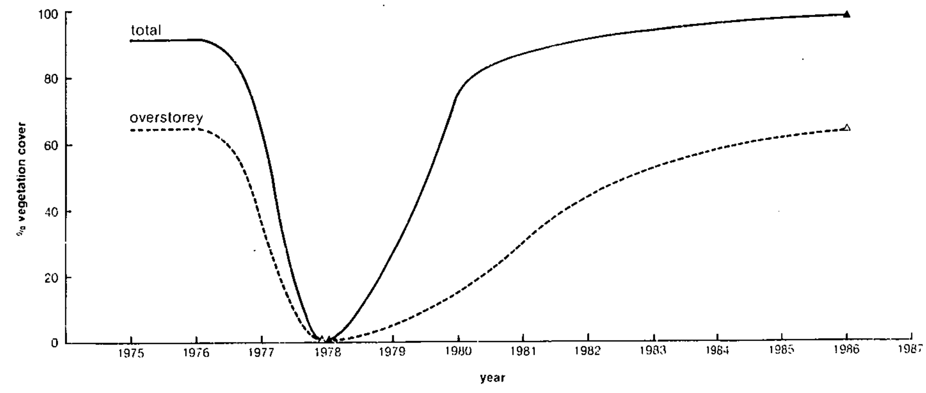
Figure 13

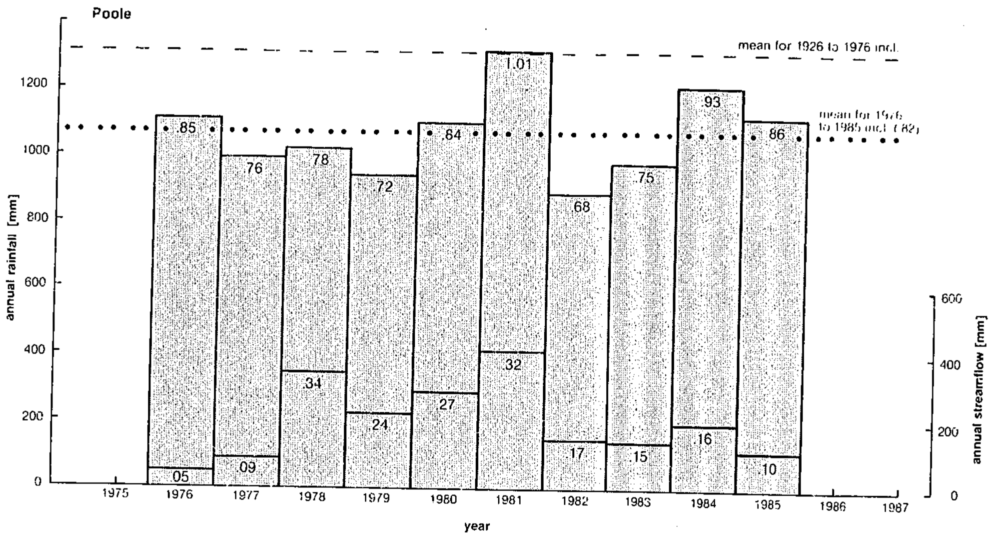
Annual values of rainfall, streamflow, flow-weighted mean stream salinity, minimum bore water level (averaged for all bores in a catchment) and vegetation cover in the four research catchments from 1975 to 1986. (The numbers at the top of the rainfall bars give the ratio between the rainfall in the respective year and the mean annual rainfall for 1926 to 1976 inclusive. The numbers at the top of the streamflow bars give the annual streamflow as a fraction of the rainfall in the respective year.)

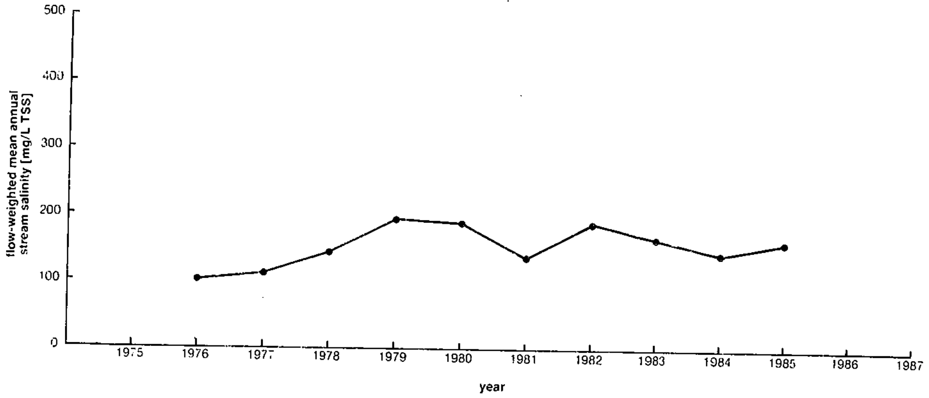

Crowea
mean for 1926 to 1976 incl.
mean for 1976 to 1985 incl. (.80)
annual rainfall [mm]
annual streamflow [mm]
1400
1200
1000
800
600
400
200
0
600
400
200
0
.77
.12
.79
.22
.79
.39
.75
.29
.86
.25
1.01
.32
.63
.26
.66
.27
22
.78
.15
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

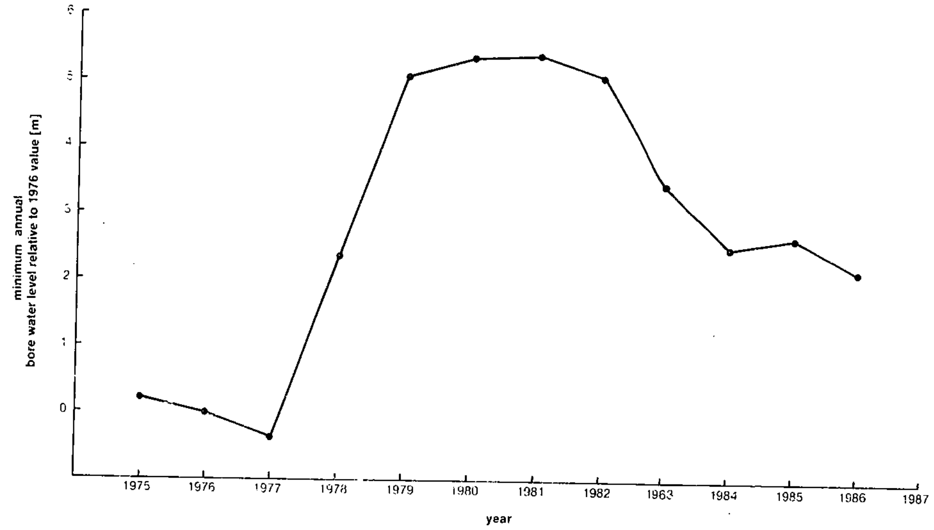

flow-weighted mean annual stream salinity [mg/L TSS]
500
400
300
200
100
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

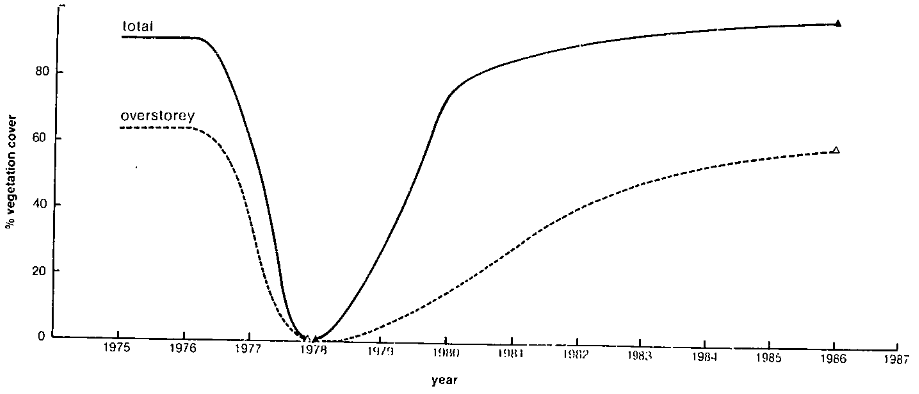

minimum annual bore water level relative to 1976 value [m]
6
5
4
3
2
1
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

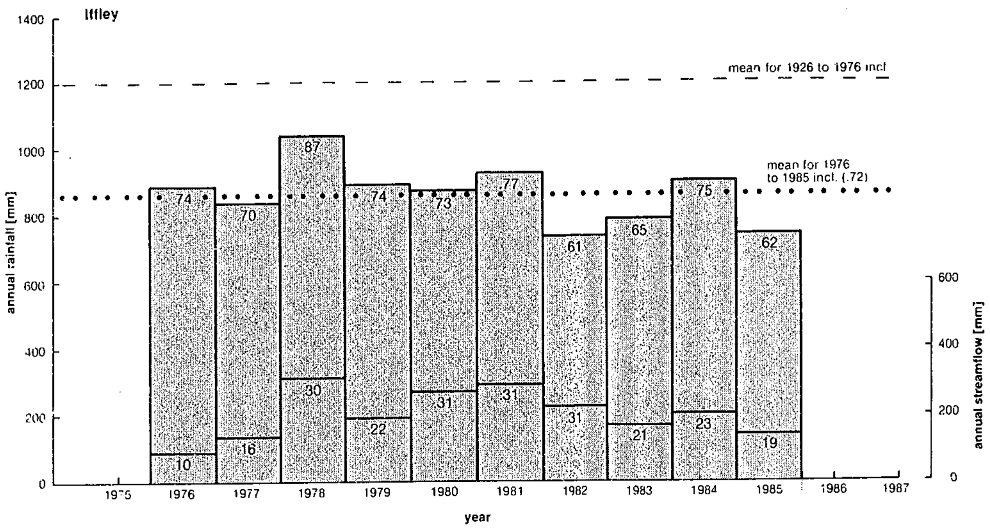

total
overstorey
% vegetation cover
100
80
60
40
20
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

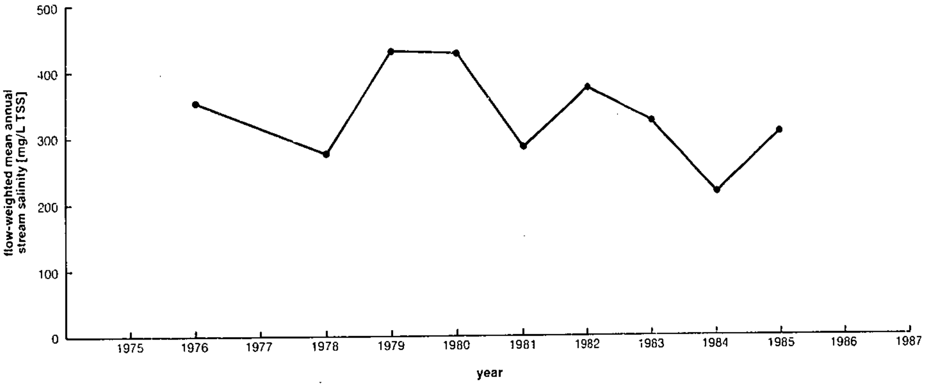

Poole
mean for 1926 to 1976 incl.
mean for 1976 to 1985 incl. (.82)
annual rainfall [mm]
1200
1000
800
600
400
200
0
annual streamflow [mm]
600
400
200
0
.85
.76
.78
.72
.84
1.01
.68
.75
.93
.86
.05
.09
.34
.24
.27
.32
.17
.15
.16
.10
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

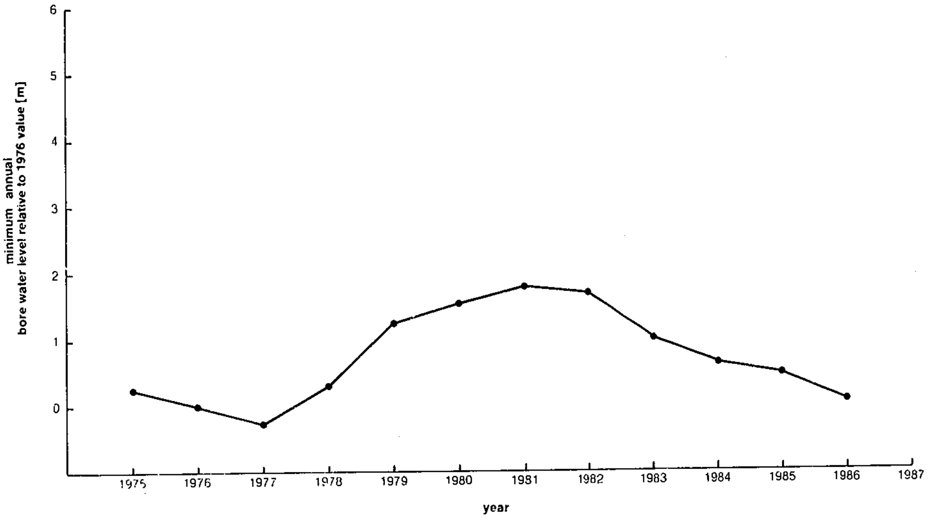

flow-weighted mean annual stream salinity [mg/L TSS]
500
400
300
200
100
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

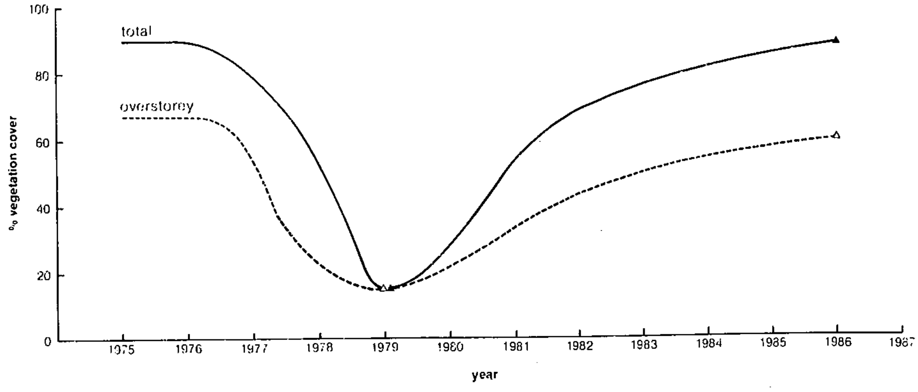

minimum annual bore water level relative to 1976 value [m]
6
5
4
3
2
1
0
1975
1976
1977
1978
1979
1980
1981
1982
1963
1984
1985
1986
1987
year

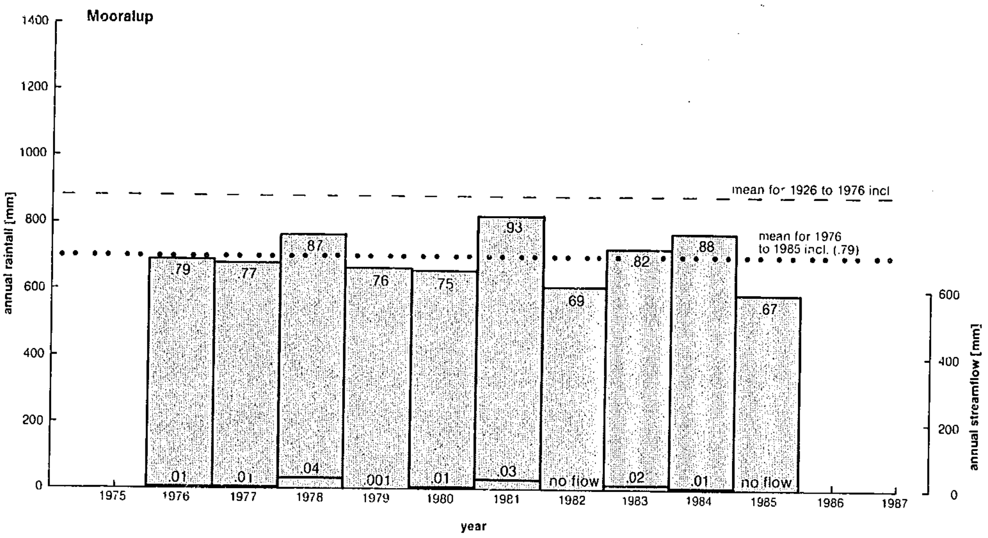

total
overstorey
% vegetation cover
80
60
40
20
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

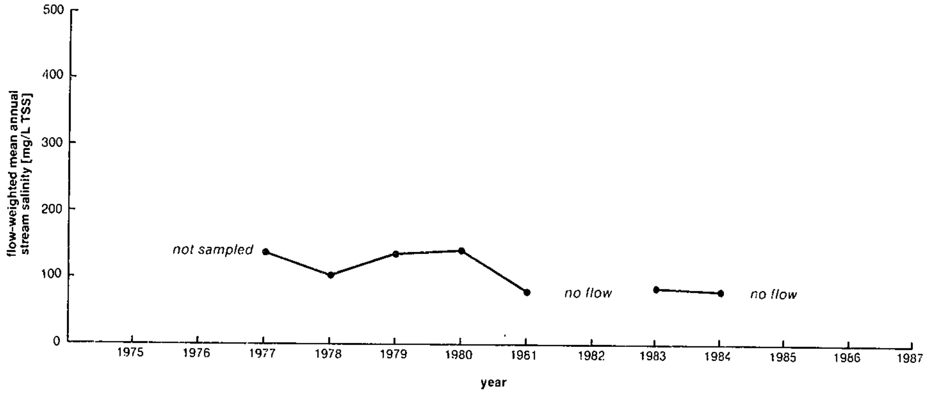

Iffley
mean for 1926 to 1976 incl
mean for 1976 to 1985 incl. (.72)
annual rainfall [mm]
annual streamflow [mm]
1400
1200
1000
800
600
400
200
0
600
400
200
0
74
70
87
74
73
77
61
65
75
62
10
16
30
22
31
31
31
21
23
19
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

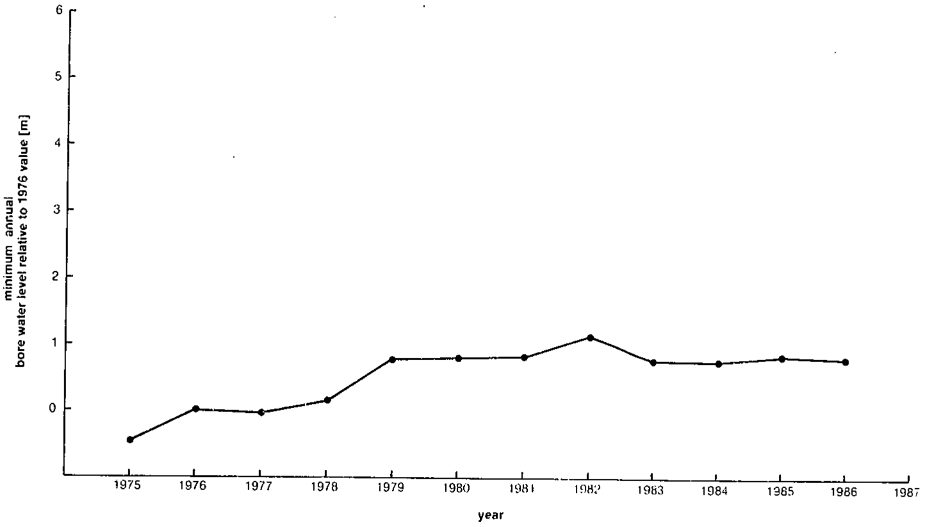

flow-weighted mean annual stream salinity [mg/L TSS]
500
400
300
200
100
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

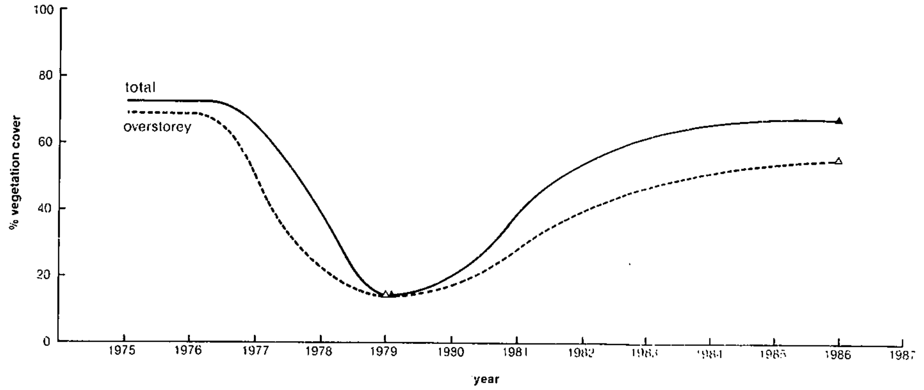

minimum annual bore water level relative to 1976 value [m]
6
5
4
3
2
1
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year


total
overstorey
% vegetation cover
100
80
60
40
20
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year


Mooralup
annual rainfall [mm]
1400
1200
1000
800
600
400
200
0
mean for 1926 to 1976 incl
mean for 1976 to 1985 incl. (.79)
.79
.77
.87
.76
.75
.93
.69
.82
.88
.67
.01
.01
.04
.001
.01
.03
no flow
.02
.01
no flow
annual streamflow [mm]
600
400
200
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year


flow-weighted mean annual stream salinity [mg/L TSS]
500
400
300
200
100
0
not sampled
no flow
no flow
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year


minimum annual bore water level relative to 1976 value [m]
6
5
4
3
2
1
0
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year


% vegetation cover
100
80
60
40
20
0
total
overstorey
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
year

Rainfall, streamflow, stream salinity, ground water level and vegetation cover are discussed in detail in the following sections.

5.2 Rainfall

The distribution of the mean annual rainfall in the southern forest region was presented in Figure 2. The isohyets are based on the average annual rainfall from 1926 to 1976 inclusive at 100 locations (Loh and King 1978). Figure 13 gives the annual rainfall measured in the four catchments during the study. These data suggest that the average annual rainfall for this period was between 17 per cent and 29 per cent below the 1926 to 1976 mean estimated from Figure 2. However, at the long-term gauging stations in the area the average annual rainfall for 1976 to 1985 was only 4 per cent to 19 per cent below the 1926 to 1976 mean (Table 6). It was suspected at first that the vegetation around the rain gauges in the experimental catchments might be the reason for this discrepancy. However, the discrepancy was similar before and after logging so that it cannot be attributed to the vegetation. Some of the difference may be due to the use of 127 mm diameter rain gauges in the research catchments while all long-term recording stations employ gauges 203 mm in diameter, or it may be due to spatial variations in rainfall.

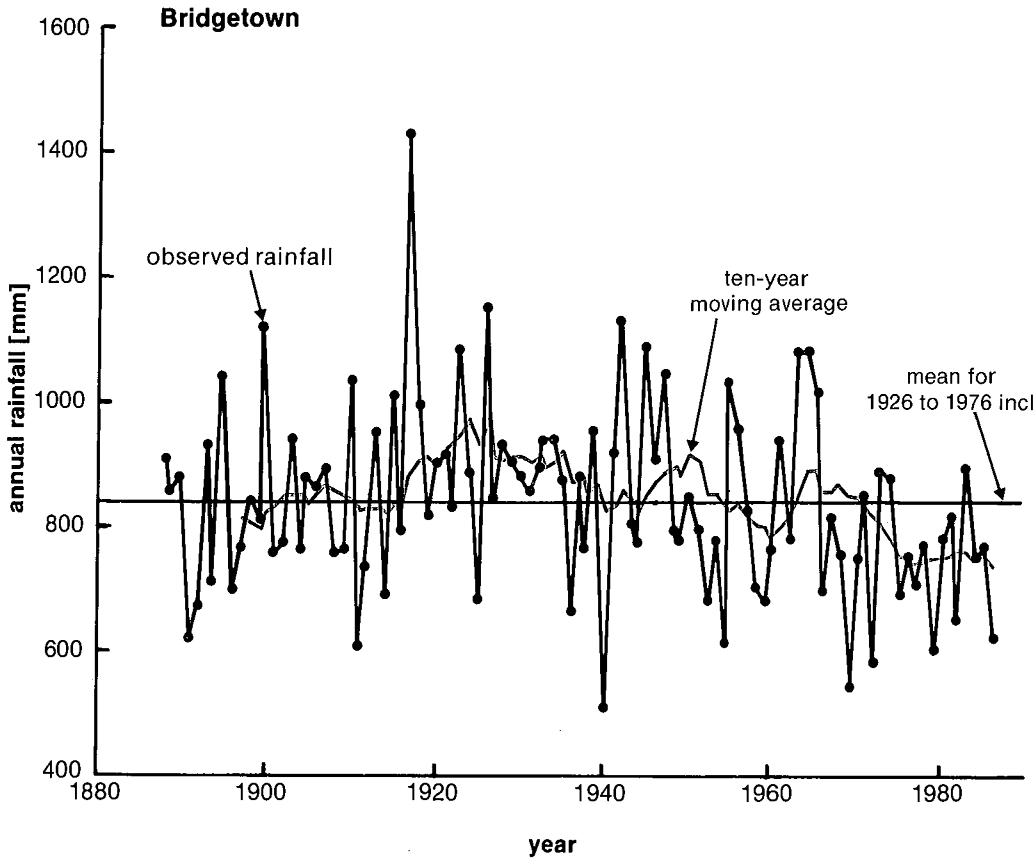
Nevertheless, the average annual rainfall during the study period was clearly below the 1926 to 1976 mean. Years with low rainfall are not unusual, but a period of below average rainfall of such length was not previously recorded in the area. This is illustrated by the annual rainfall data for Manjimup and Bridgetown plotted in Figure 14, especially the 10-year moving average. However, the rainfall records for the region are too short to determine whether the current sequence of low rainfall is really abnormal, or whether the average rainfall for 1926 to 1976 is a true representation of the

Table 6: Annual rainfall at nine long-term recording stations in the research area from 1976 to 1985. (Data from Commonwealth Bureau of Meteorology records. Gauging station locations are shown in Appendix B.)

Year	Name	Sunnywest Farm	Northcliffe	Strathalbyn	Manjimup	Glen Warren	Wilgarup	Nannup	Bridgetown	Deeside	mean for all nine stations	ratio[1]
	Gauging station no.	009512	009590	009577	009573	009550	009619	009585	009510	009530		
1976		1210	1233	1136	1022	982	941	831	758	887	1000	.91
1977		1091	1147	1147	898	910	737	739	703	776	905	.82
1978		1289	1515	1359	1053	1061	864	960	772	769	1071	.97
1979		1241	1060	1097	894	884	747	747	596	715	887	.80
1980		1180	1218	1151	924	926	802	892	782	692	952	.86
1981		1400	1498	1367	1155	1078	877	951	821	879	1114	1.01
1982		1049	1061	1085	817	804	650	1008	649	639	862	.78
1983		1182	1073	1157	969	901	845	872	894	758	961	.87
1984		1415	1334	1303	1029	1066	850	975	747	865	1065	.96
1985		986	1088	1105	913	891	768	849	773	747	902	.82
mean for 1976 through 1985		1204	1223	1191	967	950	808	882	750	773	972	.88
mean for 1926 through 1976[2]		1467	1411	1410	1039	1013	976	974	844	804	1104	1.00
ratio		.82	.87	.84	.93	.94	.83	.91	.89	.96	.88	

[1] ratio between the rainfall in the respective year and the mean annual rainfall for 1926 through 1976

[2] data from Loh and King (1978)



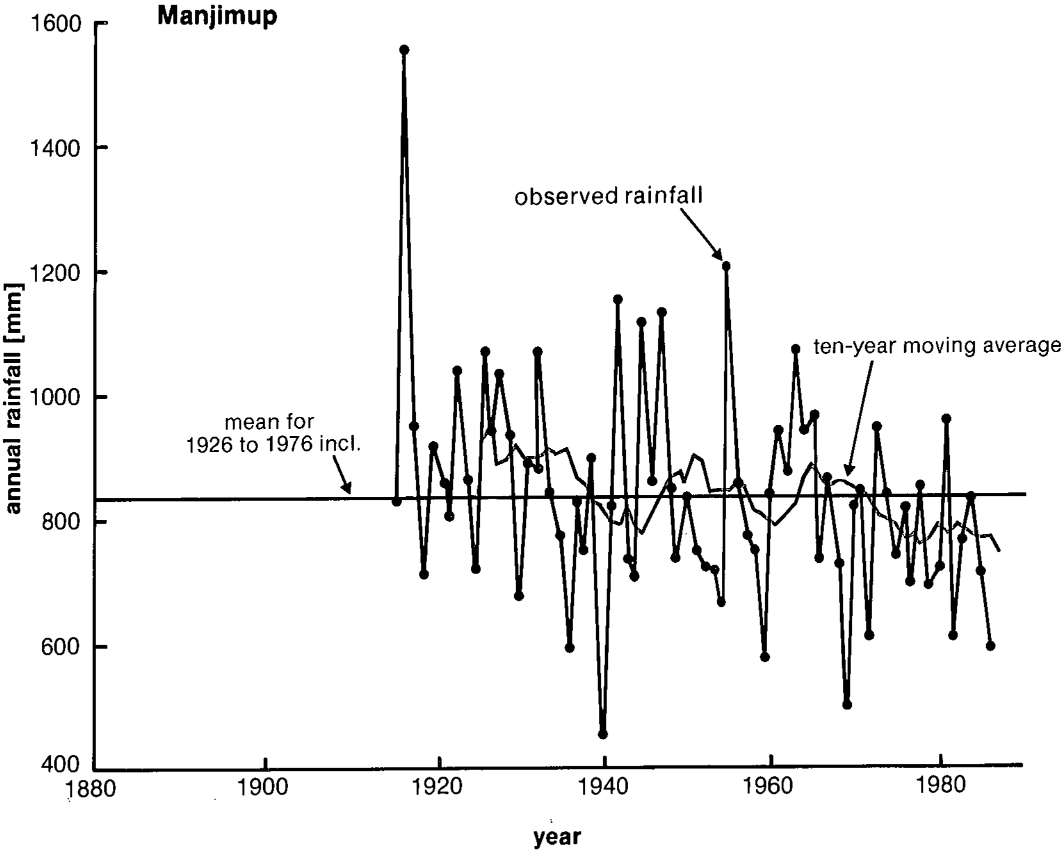


Figure 14
Annual rainfall at Bridgetown and Manjimup from the opening of the gauging stations to 1986 inclusive. (Data from Commonwealth Bureau of Meteorology records.)

long-term mean. No gauging stations existed in the region before 1887, four operated by 1900, and only 24 by 1920 (Loh and King 1978).

If the rainfall during this study was below normal, care must be taken in extrapolating the results into the future when a return to higher rainfall may alter the effects of logging on the water resources. Higher rainfall typically generates more surface and shallow subsurface runoff and hence more streamflow as well as more ground water recharge which leads to higher ground water levels. Higher ground water levels in turn lead to an increased discharge of salt to the streams. The effect on stream salinity depends on how much any increase in salt discharge is diluted by an increase in runoff.

5.3 Streamflow

All annual streamflow data presented below are given as annual streamflow volumes per unit catchment area, expressed in units of millimetres to allow direct comparisons with the annual rainfall figures. Based on the one year of pre-logging data (1976) and information from other streams nearby, typical annual streamflow under mature forest is likely to be 100 to 250 mm at Crowea, 20 to 150 mm at Poole, 50 to 200 mm at Iffley, and 0 to 50 mm at Mooralup. These values vary with the total annual rainfall and its distribution throughout the year. Annual streamflow generally increases with annual rainfall, but rainfall from December until May hardly ever generates any streamflow because it is absorbed by the soils which are usually dry during this period.

As a result of logging, the annual streamflow increased sharply for two years (1977 and 1978) in all four catchments (Fig. 13). This was most pronounced in the Crowea and Poole catchments, but less so in the Iffley and Mooralup catchments. The smaller increase at Iffley, and in particular at Mooralup can be attributed to the drier climatic conditions in these catchments.

Also, while the Crowea and Poole catchments were essentially clear-felled, significant amounts of vegetation were retained at Iffley and Mooralup which most likely further moderated the increase in streamflow.

Since 1979, concurrent with the regeneration of the cut-over areas, streamflow gradually declined again in all four catchments. This trend is somewhat obscured because streamflow tends to vary with rainfall. Expressing annual streamflow as a percentage of annual rainfall (Fig. 15) takes out some of the variation due to different rainfall amounts but does not account for differences in rainfall distribution. The data indicate that in the Crowea, Poole and Iffley catchments streamflow is likely to return to pre-logging values by about 1990, some 11 to 12 years after the beginning of regeneration. In the Mooralup catchment, where streamflow is naturally low as a consequence of low rainfall and high potential evapotranspiration, it may already be back to pre-logging levels.

The higher annual streamflow volumes at Crowea, Poole and Iffley since logging arose from increased flow rates and longer flow durations (Table 7). The situation at Mooralup is more difficult to assess. In the low rainfall zone streamflow rates are generally low and flow durations relatively short. Both are therefore quite sensitive to variations in the amount and distribution of rainfall and vary substantially between years. Considering this and the fact that there is only one year of pre-logging data for comparison, Table 7 suggests that the flow period at Mooralup was not notably affected by logging and subsequent regeneration, but that the relatively high flow rates in 1978, 1981 and 1983 were probably a consequence of logging.

The streamflow response to logging and regeneration observed in this study is consistent with observations from other parts of the world. Hibbert (1967), and more recently Bosch and Hewlett

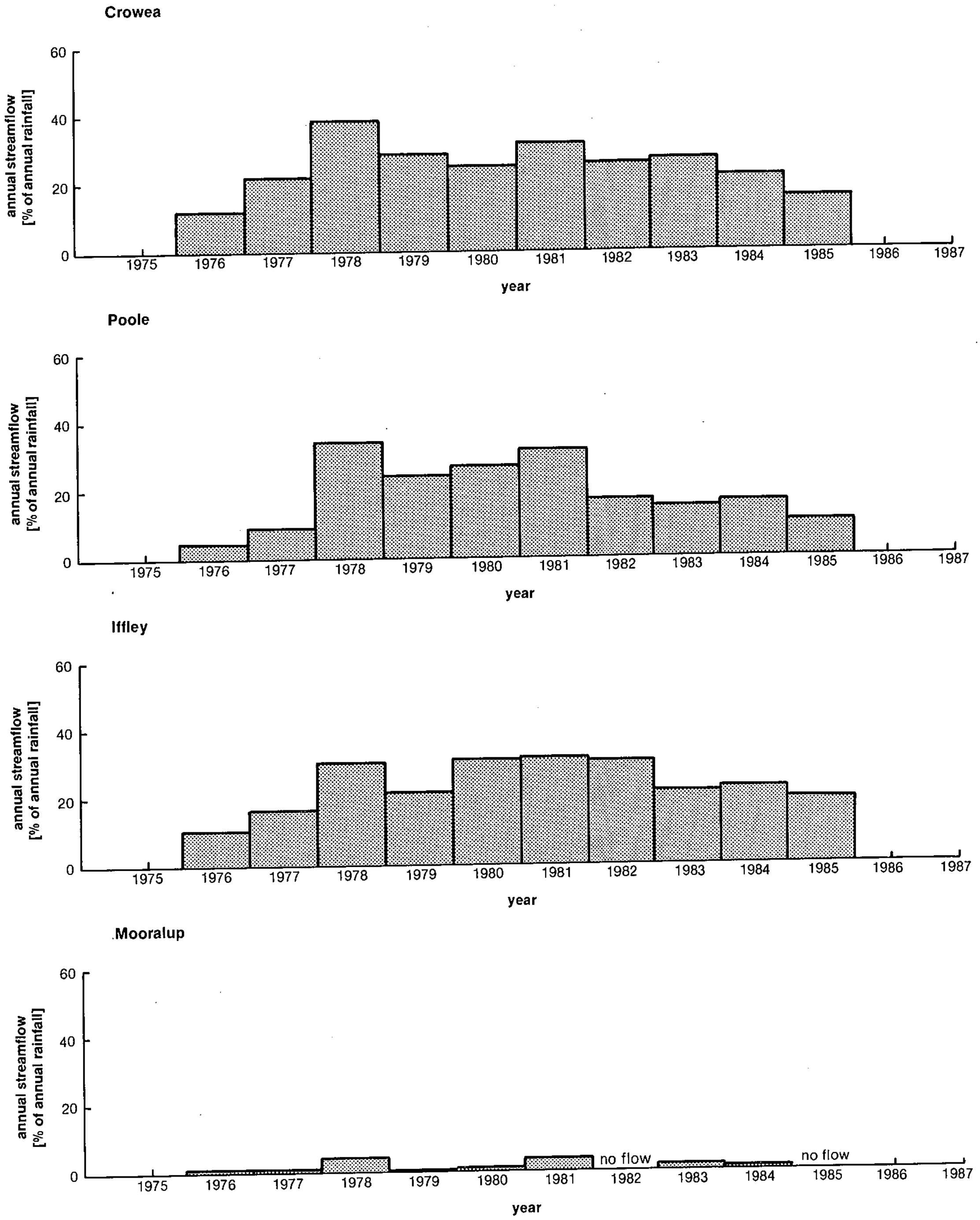


Figure 15

Annual streamflow as a percentage of annual rainfall in the four research catchments from 1976 to 1985.

Table 7: Number of days with streamflow and average streamflow rate in the four research catchments from 1976 to 1985. (The average streamflow rate was calculated by dividing the total annual streamflow volume by the number of days with flow.)

	Crowea		Poole		Iffley		Mooralup	
Year	no. of days with flow	average streamflow rate [mm/day]	no. of days with flow	average streamflow rate [mm/day]	no. of days with flow	average streamflow rate [mm/day]	no. of days with flow	average streamflow rate [mm/day]
1976	276	.46	118	.43	160	.57	130	.05
1977	235	1.02	119	.75	171	.80	122	.03
1978	365	1.15	193	1.80	219	1.44	147	.21
1979	365	.81	194	1.16	245	.79	64	.01
1980	366	.81	191	1.53	260	1.04	117	.04
1981	365	1.20	193	2.16	233	1.24	124	.22
1982	365	.61	155	.97	185	1.22	no flow	
1983	365	.67	116	1.25	150	1.11	75	.15
1984	366	.78	180	1.09	189	1.08	117	.05
1985	365	.46	89	1.31	174	.82	no flow	

(1982) reviewed a large number of data reported in the scientific literature and concluded that streamflow generally increases for one to two years after logging and then declines again as the vegetation grows back. Data from experimental catchments near Collie, about 100 km north of Manjimup, suggest that in south-west Western Australia most of the increased streamflow after logging comes from increased shallow subsurface runoff (Williamson et al. 1987).

5.4 Stream salinity

Figure 13 gives the flow-weighted mean annual stream salinity in the four research catchments during the study. All discussion here is concerned with flow-weighted mean annual stream salinity which is therefore simply referred to as stream salinity in the remainder of this section. At Crowea and Poole it roughly followed the changes in ground water level, moderated by variations in streamflow. (Recall that surface and shallow subsurface runoff generate most of the flow, and that ground water generates most of the salinity.) From 1976 to 1979, concurrent with the rise in ground water level as a result of logging, stream salinity increased by 50 mg/L TSS at Crowea, and by 94 mg/L TSS at Poole. The bigger increase at Poole most likely resulted from the bigger rise in ground water level (see section 5.5). Except in 1981 when it was lowered by high flow volumes, stream salinity in both catchments remained near the 1979 value until 1982-83 while the ground water levels were high, but then fell again as the ground water levels declined. The fall in 1984 might have been amplified by the greater streamflow volume in that year. The slight increase in stream salinity in 1985 was probably mostly a response to the drop in streamflow rather than the small rise in ground water level.

The rise in stream salinity and its temporary persistence at an elevated level after logging occurred despite increased streamflow. This means that the amount of salt released by the raised ground water levels was proportionally larger than the amount which could be fully diluted by the increase in streamflow. Nevertheless, even at its highest point stream salinity was less than 200 mg/L TSS, which is far below the 500 mg/L TSS considered to be the upper limit for high quality drinking water. The temporary increases of 50 and 94 mg/L TSS observed at Crowea and Poole were therefore not a significant deterioration of stream water quality.

At Iffley logging did not significantly influence the ground water level until 1979. Hence stream salinity decreased from 1976 to 1978 in response to the increase in streamflow volume. The elevated stream salinities in 1979 and 1980 on the other hand were due to the raised ground water level. No explanation was obvious for the drop in 1981. Considering the combination of ground water level and streamflow volume, stream salinity in 1982 should have been higher, too. Its decline in 1983 and 1984 was consistent with the decline in ground water level, and in 1984 was possibly assisted by the higher streamflow. Lower streamflow probably caused the stream salinity rise in 1985.

Prior to logging (1976) the stream salinity at Iffley was 352 mg/L TSS. In 1979, at its highest level after logging, it reached 432 mg/L TSS, 80 mg/L above the pre-logging value. This is a tolerable increase because stream salinity remained below 500 mg/L TSS. Since 1983, the fourth year after the beginning of regeneration, it was less than the pre-logging value.

The temporary increase in stream salinity after logging was of similar magnitude in the Crowea, Poole and Iffley catchments. However, the total stream salinity at Iffley was about twice as high. Comparison with Table 3 shows that the stream salinity level at Iffley is uncharacteristically high for forested catchments in the region. This is probably due to topographic and geologic features at Iffley (Martin 1980) to which Johnston _et al_. (1980) also attribute the unusually high soil salt storages for a catchment with 1200 mm mean annual rainfall (Fig. 10).

In the Mooralup catchment stream salinity was not influenced by changes in ground water level and only responded to variations in streamflow. The highest observed value was 142 mg/L TSS in 1980. No pre-logging data were available for this area so that it cannot be ascertained how logging influenced stream salinity. However, at well below 200 mg/L TSS, stream salinity at Mooralup is not a concern. Throughout the study period the lowest stream salinities were observed in the Mooralup catchment, despite its location in the low rainfall zone which prior to this research was considered to be the most likely region where logging might lead to high stream salinities.

If streamflow and ground water return to the level they would have been at had there been no logging, then stream salinity should do the same. At Crowea and Poole this is likely to happen in the early 1990s. The available ground water data do not permit such an assessment for the Iffley catchment. Stream salinity at Mooralup did not respond to changes in ground water level and therefore probably did not increase after logging in the first place. It may even have decreased slightly as a result of the increase in streamflow.

5.5 Ground water

Variations in the amount and distribution of the annual rainfall strongly influence the maximum ground water level in a given year. The minimum ground water level is less affected and thus better represents changes in ground water storage from year to year. At times, some bores also had surface or shallow subsurface runoff flowing directly into them, which distorts the bore water level. It eventually equilibrates with the ground water as the runoff water seeps from the bore into the surrounding soil. Minimum bore water levels are generally not affected by this problem since they usually occur in the dry season when runoff hardly ever takes place. The lowest water level in each bore was therefore chosen to represent the ground water status in a given year. Note that bore holes provide an easy pathway for vertical ground water movement. Bore water levels therefore represent the height to which ground water would rise if there were a non-restrictive flowpath. If a zone of low permeability retards vertical ground water movement bore water levels do not correspond to the actual position of the ground water. This was the case in some areas at Crowea and Iffley where no water was ponded on the soil surface although the bore water levels were above the soil surface.

To summarise the ground water response the yearly minimum water levels of all bores in a catchment were averaged. Only bores which contained water throughout the study period were considered. This was the case for six bores at Crowea, eight at Poole, nine at Iffley and one at Mooralup. The deviations from the 1976 value are plotted in Figure 13. At Crowea the average minimum bore water level rose immediately after logging, remained at an elevated but fairly constant level from 1979 to 1982 and then declined again. The pattern at Poole and Iffley was similar, except that the bore water levels decreased a little in 1977 before they started to rise. The slight increase at Crowea and Poole in 1985 was caused by the relatively high rainfall in the winter of 1984. All but one bore in the Mooralup coupe were dry. The level in that bore also fell slightly in 1977 and then increased. However, since 1979 it remained virtually unchanged.

The limited ground water response at Mooralup was most likely a result of the dry climatic conditions in the area, low rainfall combined with high potential evapotranspiration, coupled with the fact that not all the vegetation was removed during logging. Although the Iffley catchment is in a drier location than the Crowea and Poole catchments, its comparatively small ground water response was presumably partly due to the retained vegetation, too. Regeneration at Crowea and Poole began in mid 1978, but not until late 1979 at Iffley, which is probably why its average minimum bore water level peaked later. Soils, geology and topography also influence the ground water system and were most likely the cause for the larger response at Poole though Crowea has the wetter climate.

Figure 13 shows that by 1986 the average minimum bore water level at Iffley was almost back to its pre-logging value, while it was still considerably higher in the other three catchments. However, minimum bore water levels are also influenced by annual variations in rainfall and evapotranspiration. As a result of below average rainfall control bore water levels in the southern forest have generally declined from 1976 to 1986 (Table 8). The bore water levels in the four research catchments are therefore farther above the level they would be at had there been no logging than Figure 13 suggests.

Table 8: Deviation of the 1986 minimum bore water level from the 1976 minimum bore water level for several groups of control bores in the research area.

Catchment	Change in bore water level [m]
Lewin North[1]	- .74
April Road South[1]	-1.11
Yerraminnup North[1]	- .44
Crowea	- .64
Poole	- .44
Iffley	-2.51

[1] data from Borg and Loh (1987)

Water levels in the bores within each catchment are subject to climatic variations, plus those caused by logging. The bores installed in forested areas adjacent to the four catchments, hereafter called control bores, were intended to monitor fluctuations due to rainfall and evapotranspiration. The difference in water level between those two groups of bores represents the net effect of logging.

The control bores near the Mooralup catchment were dry. The ones near the Iffley catchment were placed in an area logged sometime between 1961 and 1970 using light selection cutting. When the bores were constructed in 1975 it was thought that the previous relatively light logging would no longer influence the bore water level. However, the water level in the Iffley control bores fell considerably more than in any other group of control bores in the region (Table 8). This suggests that regeneration still affected the ground water level. No valid comparisons could therefore be made between the bores in the Iffley catchment and its respective control bores.

The control bores near the Crowea and Poole catchments were placed in virgin forest and therefore truly reflect variations in ground water level due to rainfall and evapotranspiration. The difference in minimum water levels between control and catchment bores at Crowea and Poole is shown in Figure 16. Extrapolation from the last three data points suggests that around 1991, 13 years after the start of regeneration, the bore water levels at Crowea and Poole will reach the level they would have been at had the catchments not been logged.

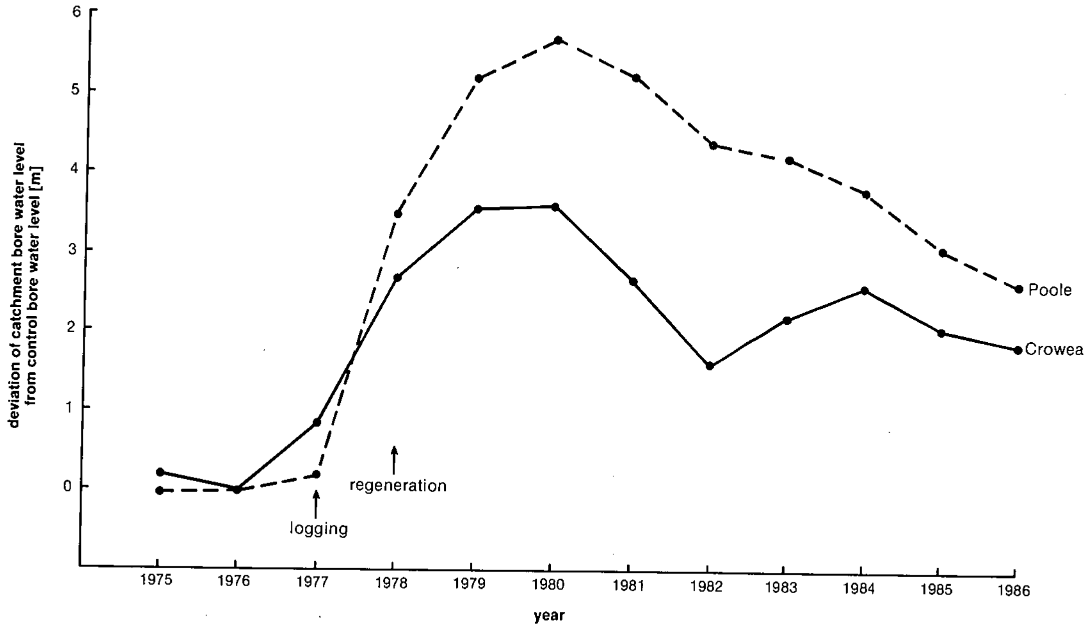


Figure 16
Deviation of the minimum water level of the Crowea and Poole catchment bores from the minimum water level of the corresponding control bores from 1975 to 1986. (The deviation for 1976 was set equal to zero and all others scaled accordingly. The minimum water level for each group of catchment bores was obtained by averaging the minimum water level of all bores in the catchment. The minimum water level for each group of control bores was obtained by averaging the minimum water level of all bores in the group.)

However, the information in this Figure should be viewed with some caution. Several years of pre-logging data are necessary to accurately relate the water level response in control bores to that of catchment bores. No such data were collected in this study so that a one to one relationship was assumed, despite the fact that events leading to a unit change in bore water level in one area rarely cause the same magnitude of change in another area, even if it is nearby (Borg et al. 1987). This may be the reason for the dip observed at Crowea between 1980 and 1984. During this period the water level in the control bores underwent a pronounced rise and fall while it declined continuously in most catchment bores.

There are some data on the effect of logging and regeneration on ground water levels reported in the scientific literature. As in this study, they also show that ground water levels rise for some time after logging and decline again as the cut-over areas regenerate (Wilde et al. 1953; Trousdell and Hoover 1955; Heikurainen 1967; Holstener-Jorgensen 1967, 1978; Williams and Lipscomb 1981; Sharma et al. 1982; Biddiscombe et al. 1985).

When ground water rises into a salt bulge in the soil profile, ground water salinity increases. If it rises further, or in a soil profile where salinity increases with depth, ground water salinity decreases. A rise (or fall) in ground water level can thus lead to an increase or decrease in ground water salinity. The rise and fall of the bore water levels in the four research catchments had no discernable influence on bore water salinity. Salinity data for all bores are listed in Appendix I. Because there are seasonal fluctuations in bore water levels and hence bore water salinities, annual minimum and maximum values are given. Note that some values, especially maximum ones, may have been distorted by surface and shallow subsurface runoff entering a bore.

6. REGROWTH OF VEGETATION COVER

Logging causes a disturbance of the water and salt regime of a catchment. How fast and how far these disturbances can be reversed depends on how quickly and how well the vegetation, and hence transpiration, recovers. Prior to logging the net change in soil and ground water storage from year to year is very small and the annual evapotranspiration can be estimated as rainfall minus streamflow. For several years after logging changes in water storage are significant and evapotranspiration can no longer be evaluated like that. Estimating transpiration by other means from a forest area is difficult and was not attempted in this study, but some information can be deduced from vegetation density. A survey was therefore conducted in 1986 to evaluate the density and structure of forests that have regenerated in areas which were clear-felled or experienced heavy selection cutting. Several unlogged areas were sampled as well to determine forest density and structure typical of unlogged forest. The four experimental catchments from this study and the seven from the paired catchment study are included in the survey. The methods and full results are given by Stoneman _et al_. (1987). This report discusses only some of the implications for water use.

Transpiration from a catchment is determined by the combination of meteorological conditions, transpiring area, available water and water transport from the soil to the leaves and from the leaves into the air. Vegetation cover is a measure of the transpiring area. Its changes after logging are depicted in Figure 17 for three combinations of forest type and rainfall zone. All tree species are referred to as overstorey and all other vegetation as understorey. 'Cover' refers to the percentage of ground area covered by a vertical projection of the overstorey or total vegetation canopy onto the ground surface.

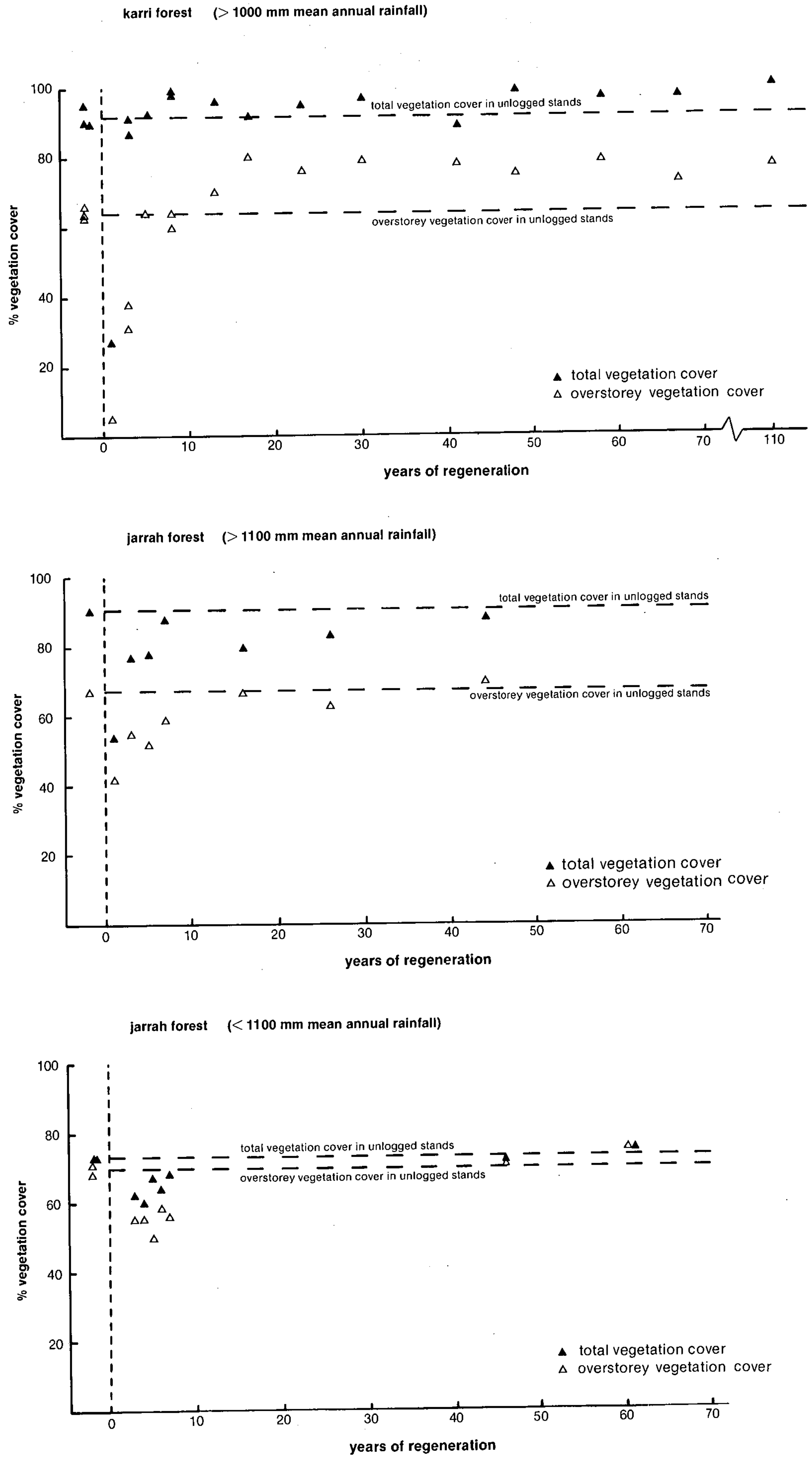


Figure 17

Regrowth of vegetation cover after logging with time in karri forest with more than 1000 mm mean annual rainfall, jarrah forest with more than 1100 mm mean annual rainfall, and jarrah forest with less than 1100 mm mean annual rainfall. (Data from Stoneman et al. 1987.)

The overstorey cover in karri regrowth forests reached the value for unlogged areas about ten years after the start of regeneration. It continued to increase for another ten years and then appeared to stabilise at around 75 to 80 per cent, well above the 60 to 70 per cent common in unlogged stands. Total vegetation cover reached the unlogged value in about five years, continued to rise for another five years, and since then has remained about five per cent above that of unlogged stands. The relatively low values for the data points 17 and 41 years after regeneration were caused by controlled fuel reduction burns which were carried out less than two years before sampling.

In jarrah forest, independent of rainfall, the overstorey cover exceeded 70 per cent of the value in unlogged stands within five years after the beginning of regeneration, 90 per cent within ten years, and reached the unlogged value in about 20 to 30 years. The recovery in terms of total vegetation cover was similar. It is not clear from the data whether the vegetation cover of jarrah regrowth forest will eventually exceed that of unlogged stands. The overstorey cover was similar in all rainfall zones. However, the amount of understorey vegetation decreased with decreasing mean annual rainfall.

Given a similar species and age distribution, similar site conditions and an adequate supply of water, evapotranspiration increases with vegetation cover (Brookes 1950; Langford and O'Shaughnessy 1979). However, in most of south-west Western Australia annual evapotranspiration from forest is limited by a lack of water (Fig. 18). In winter, when potential evapotranspiration is low and most of the rainfall occurs, there is usually no shortage of water. In summer, on the other hand, when potential evapotranspiration is high and little rainfall occurs, actual evapotranspiration is governed by the amount of water stored in the soil. This amount is generally smaller than that which could be removed by evapotranspiration and is therefore consumed faster the higher the percentage of

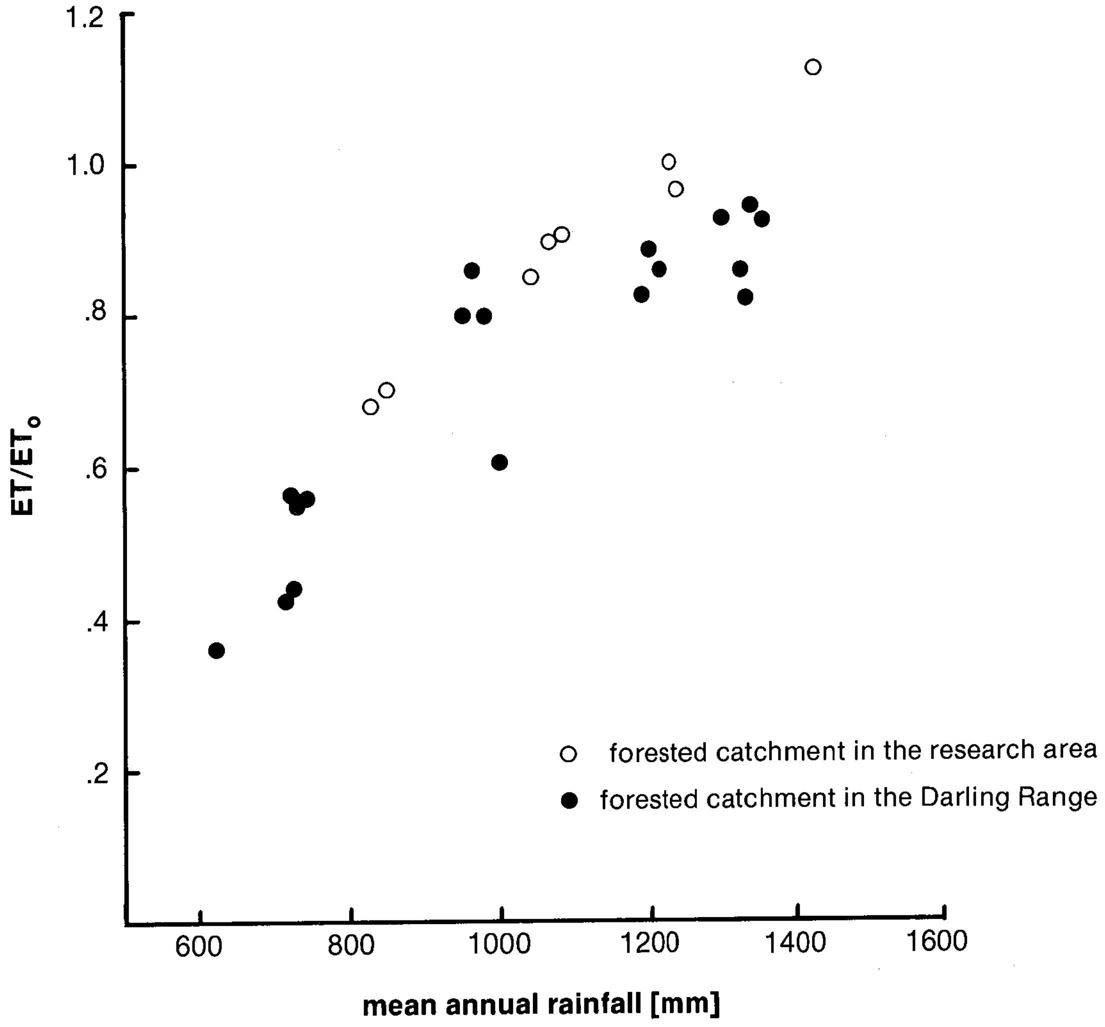


Figure 18

The ratio of actual annual evapotranspiration (ET) to potential annual evapotranspiration (ET_0) in relation to mean annual rainfall in forested catchments in south-west Western Australia. (Based on Loh 1982. Actual evapotranspiration was estimated as annual rainfall minus annual streamflow. Potential evapotranspiration was estimated as .85 x annual pan evaporation following .)

vegetation cover is. In south-west Western Australia a one per cent difference in vegetation cover thus normally translates into less than a per cent difference in annual evapotranspiration.

The extent of the root system partly determines the amount of soil water available to a plant. Roots of mature jarrah and marri trees may reach depths in excess of 20 m, but 90 per cent of all roots are in the top 2 m of the soil profile, and 99 per cent in the top 5 m (Carbon et al. 1980; Dell et al. 1983). There are no studies on the root distribution of karri, but its roots can also grow to a depth of 20 m or more (Campion 1926). No studies exist on the root development with time for either species, but judging from other plants the roots of these eucalypts are likely to explore the top 1 to 3 m of the soil profile within a year, and the top 5 m within three to five years (Weaver 1920; Borg and Grimes 1986). Some roots will grow deeper as the plants mature.

The annual fluctuations in ground water level in the southern forest demonstrate that water is removed from substantial depths, though it is not known how much flows through the soil into the upper parts of the soil profile where it is subsequently removed by shallow roots, how much is removed directly by deep roots, and how much is removed by lateral flow. With greater depth below the soil surface roots become fewer, temperature and oxygen concentration lower, and salinities higher, which creates increasingly unfavourable conditions for water uptake by plant roots (Taylor 1983). Furthermore, there is a resistance to water flow in roots which increases with the distance water travels inside the roots. The magnitude of this resistance for eucalypts has not been studied, but if it is large water uptake from greater depths may be severely inhibited (Passioura 1972; Taylor and Klepper 1978). Direct water uptake by jarrah, marri and karri roots from below 5 m is therefore probably small. While the lack of data does not permit any definite conclusions it seems likely that the amount of soil water available to a regrowth forest three to five years after regeneration is nearly the same as for a mature forest.

Tree trunks also have a resistance to water flow which is proportional to tree height (Hellkvist et al. 1974). To get water to the leaves tall mature trees must overcome a higher lift as well as a higher resistance than short young trees. Data for mountain ash in Victoria further suggest that the resistance per unit height of tree may be higher in old than in young trees (Legge 1985 a,b). Even if there is no shortage of available soil water, mature trees may therefore not be able to supply water to the leaves as fast as it can be lost, especially on warm, dry days. The result is a reduction in stomatal opening and transpiration. During winter, young trees may thus transpire more water per unit cover than mature trees. This may be the case during summer, too, or the younger trees may just use the available water faster. So, it is possible that a young regrowth forest with smaller vegetation cover than an adjacent mature forest may consume as much or even more water.

From the available data it is not possible to determine how much water regrowth areas actually use compared with mature forest. However, the bore water level data presented above demonstrate that within five years after the beginning of regeneration the regrowth forests start to deplete the additional ground water storage which has accumulated since logging.

In forested catchments in Victoria it was observed that, after several years of regeneration, streamflow in regrowth stands was less than in the mature stands they had replaced (Brookes 1950; Brookes and Turner 1963; Kuczera 1985). This was apparently due to higher transpiration from the regenerating stands (Langford 1976) although there were no obvious differences in vegetation density (Kuczera 1985). No such response has yet been observed in the southern forest of Western Australia which may at least in part be due to the absence of suitable streamflow information. Nevertheless, it is a distinct possibility in regenerating jarrah stands and especially in regenerating karri stands since the latter attain a higher vegetation density than unlogged stands. Should a reduction in streamflow from regrowth stands occur they can be thinned to reduce transpiration which leads to an increase in streamflow (Shea _et_ _al_. 1975; Stoneman, Schofield and Bartle 1987). The assessment of the long term influence of forest regeneration on streamflow is an objective of the paired catchment studies mentioned in the introduction. The four catchments discussed in this report could not be used for this purpose. They were intended to provide an early indication of the hydrologic response to the revised cutting strategies and subsequent regeneration. As a result of this objective streamflow data were collected for only one year prior to logging which is not a sufficient base to judge how future streamflows compare to pre-logging values. Furthermore, the lack of calibration with nearby, uncut control catchments would not allow one to accurately separate changes in streamflow caused by changes in vegetation cover from changes brought about by variations in climate.

7. ACKNOWLEDGEMENTS

The authors wish to thank the following people at the Water Authority of Western Australia and the Department of Conservation and Land Management W.A. for their help in producing this report:

Sue Graham, Karen Lemnell and Carlene Pearson for typing the manuscripts; Robyn Mundy, Michael Briggs and Mark Bozikovic for drawing the figures; Gary Olley, Des Muir, Annette Turpin and Bob Symons for producing the catchment maps; Kim Phillips-Jones, Pat Collins, Peter Stirling and Alan Lush for providing land use, vegetation and logging details; Ian Loh, Nick Schofield, John Bartle, Jack Bradshaw, Michael Martin and Roger Underwood for technical discussions and reviewing the manuscript; Marianne Lewis for editing it; Peter van de Wyngaard for getting it ready for printing; and Brad Fuller, Greg May, Trevor York, Frank Davies, Debbie Cunningham, Robert Stokes, Allan Waugh, Colin Cicero and Sweton Stewart for various small but essential contributions.

8. REFERENCES

BIDDISCOMBE, E.F., ROGERS, A.L., ALLISON, H. and LITCHFIELD, R. (1985). 'Response of groundwater levels to rainfall and to leaf growth of farm plantations near salt seeps.' Journal of Hydrology 78:19-34.

BORG, H. and GRIMES, D.W. (1986). 'Depth development of roots with time : An empirical description.' Transactions of the American Society of Agricultural Engineers 29:194-197.

BORG, H., King, P.D., and LOH, I.C. (1987). 'Stream and ground water response to logging and subsequent regeneration in the southern forest of Western Australia. Interim results from paired catchment studies.' Water Authority of W.A., Water Resources Directorate, Hydrology Branch Report WH 34.

BOSCH, J.M. and HEWLETT, J.D. (1982). 'A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration.' Journal of Hydrology 55:3-23.

BRADSHAW, F.J. (1985). 'Silvicultural guidelines for the treatment of even-aged regrowth and two-tiered karri forests.' Department of Conservation and Land Management W.A., Technical Report No. 1.

BRADSHAW, F.J. (1986). 'Silvicultural guidelines for virgin southern jarrah forest.' Department of Conservation and Land Management W.A., Technical Report No. 4.

BRADSHAW, F.J. and LUSH, A.R. (1981). 'Conservation of the karri forest.' Forests Department of Western Australia.

BROOKES, J.O. (1950). 'The relation of vegetative cover to water yield in Victorian mountain watersheds.' M. Sc. Thesis, University of Melbourne.

BROOKES, J.O. and TURNER, J.S. (1963). Hydrology and Australian forest catchments. In Australian Academy of Science, 'Water resources - use and management.' Proceedings of a Symposium at Canberra, A.C.T. Melbourne University Press, Melbourne.

BURVILL, G.H. (1947). 'Soil salinity in the agricultural areas of Western Australia.' Journal of the Australian Institute of Agricultural Science 13:9-19.

CAMPION, W.E. (1926). 'The depth attained by roots.' Australian Forestry Journal 9:128.

CARBON, B.A., BARTLE, G.A., MURRAY, A.M. and MACPHERSON, D.K. (1980). 'The distribution of root length, and the limits to flow of soil water to roots in a dry sclerophyll forest.' Forest Science 26:656-664.

CHURCHILL, D.M. (1967). 'The distribution and prehistory of *Eucalyptus diversicolor* F. Muell., *E. marginata* Donn Ex Sm., and *E. calophylla* R. Br. in relation to rainfall.' Australian Journal of Botany 16:125-151.

COLLINS, P.D.K. and BARRETT, D.F. (1980). 'Shannon, Warren and Donnelly river basins water resources survey.' Engineering Division, Public Works Department of Western Australia, Water Resources Branch Report No. W.R.B. 6.

DELL, B., BARTLE, J.R. and TACEY, W.H. (1983). 'Root occupation and root channels of jarrah forest subsoils.' Australian Journal of Botany 31:615-627.

DEPARTMENT OF HEALTH (1980). 'Desirable quality for drinking water in Australia.' Australian Government Publishing Service, Canberra.

FALLICK, C.J. (1987). 'Pulping research activities in Western Australia.' CSIRO, Divison of Chemical and Wood Technology, Forest Products Newsletter (in press).

FORESTS DEPARTMENT OF WESTERN AUSTRALIA (1973). 'Environmental impact statement on the woodchipping industry agreement proposals for Western Australia.'

HATCH, A.B. (1976). 'The relationship between electrical conductivity of soil : water suspensions and soluble salts in some Western Australian forest soils.' Forests Department of Western Australia, Research Paper No. 19.

HEIKURAINEN, L. (1967). Effect of cutting on the ground-water level on drained peatlands. In Sopper, W.E. and Lull, H.W. (eds.), 'Forest Hydrology.' Pergamon Press, New York. pp 345-354.

HELLKVIST, J., RICHARDS, G.P. and JARVIS, P.G. (1974). 'Vertical gradients of water potential and tissue water relations in Sitka spruce trees measured with the pressure chamber.' Journal of Applied Ecology 11:637-668.

HERBERT, E.J. and RITSON, P. (1976). 'Small streamflow measurements in the northern jarrah forest, Western Australia.' Forests Department of Western Australia, Research Paper No. 28.

HIBBERT, A.R. (1967). Forest treatment effects on water yield. In Sopper, W.E. and Lull, H.W. (eds.), 'Forest Hydrology.' Pergamon Press, New York. pp 527-543.

HILLEL, D. (1982). 'Introduction to soil physics.' Academic Press, New York.

HINGSTON, F.J. and GAILITIS, V. (1975). 'Salts in rainfall in Western Australia (1973-74).' Unpublished compilation of data.

HINGSTON, F.J. and GAILITIS, V. (1976). 'The geographic variation of salt precipitated over Western Australia.' Australian Journal of Soil Research 14:319-335.

HOLSTENER-JORGENSEN, H. (1967). Influences of forest management and drainage on ground-water fluctuations. In Sopper, W.E. and Lull, H.W. (eds.), 'Forest Hydrology.' Pergamon Press, New York. pp 325-333

HOLSTENER-JORGENSEN, H. (1978). 'The influence of young beech, oak and Norway spruce on the ground-water table in clayey moraine.' The Danish Forest Experiment Station, Report No. 36:222-228.

HOOKEY, G.R. (1987). 'Prediction of delays in groundwater response to catchment clearing in south-western Australia.' Journal of Hydrology (in press).

JOHNSTON, C.D. (1981). 'Salt content of soil profiles in bauxite mining areas of the Darling Range, Western Australia.' CSIRO, Land Resources Management Technical Paper No. 8.

JOHNSTON, C.D., McARTHUR, W.M. and PECK, A.J. (1980). 'Distribution of soluble salts in soils of the Manjimup Woodchip Licence Area, Western Australia.' CSIRO, Land Resources Management Technical Paper No. 5.

KUCZERA, G. (1985). 'Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest.' Melbourne and Metropolitan Board of Works, Report No. MMBW-W-0014.

LANGFORD, K.J. (1976). 'Change in yield of water following a bushfire in a forest of Eucalyptus regnans.' Journal of Hydrology 29:87-114.

LANGFORD, K.J. and O'SHAUGHNESSY, P.J. (1979). 'Soil moisture depletion rates in 1939 regrowth mountain ash over a summer drying period.' Melbourne and Metropolitan Board of Works, Report No. MMBW-W-0008.

LEGGE, N.J. (1985a). 'Anatomical aspects of water movement through stems of mountain ash (Eucalyptus regnans F. Muell.).' Australian Journal of Botany 33:287-298.

LEGGE, N.J. (1985b). 'Relating water potential gradients in mountain ash (Eucalyptus regnans F. Muell.) to transpiration rate.' Australian Journal of Plant Physiology 12:89-96.

LOH, I.C. (1982). 'Annual water balance estimates of evapotranspiration in south Western Australia.' A working paper presented at the CSIRO workshop on evapotranspiration from plant communities, Bunbury, Western Australia.

LOH, I.C. and KING, B. (1978). 'Annual rainfall characteristics of the Warren, Shannon and Donnelly River Basins.' Public Works Department of Western Australia, Water Resources Technical Report No. 78.

LOH, I.C., VENTRISS, H.B. and COLLINS, P.D.K. (1983). Water resources quality in Western Australia. In Water Research Foundation of Australia, 'Water quality - its significance in Western Australia'. Proceedings of a seminar at Murdoch University, Perth, Western Australia.

MARTIN, M.W. (1980). 'Hydrogeology of the Iffley coupe.' Geological Survey of Western Australia, Hydrogeology Report No. 2197.

McARTHUR, W.M. and CLIFTON, A.J. (1975). 'Forestry and agriculture in relation to soils in the Pemberton area of Western Australia.' CSIRO, Division of Soils, Soils and Land Use Series No. 54.

McKINNELL, F.H. (1982). 'Forest terminology in Western Australia.' Forests Department of Western Australia, Technical Paper No. 1.

MOUNT, A.B. (1964). 'The interdependence of eucalypts and forest fires in southern Australia.' Australian Forestry 28:166-172.

NATIONAL HEALTH AND MEDICAL RESEARCH COUNCIL, AND AUSTRALIAN WATER RESOURCES COUNCIL (1986). 'Guidelines for drinking water quality in Australia.' Unpublished draft of November 1986.

PASSIOURA, J.B. (1972). 'The effect of root geometry on the yield of wheat growing on stored water.' Australian Journal of Agricultural Research 23:745-752.

PECK, A.J. and HURLE, D.H. (1973). 'Chloride balance of some farmed and forested catchments in south Western Australia.' Water Resources Research 9:648-657.

Public Works Department of Western Australia, Water Resources Branch (1984). 'Streamflow records of Western Australia to 1982.' Volume 1.

RHOADES, J.D. (1974). Drainage for salinity control. In Schilfgaarde, J. van (ed.), 'Drainage for Agriculture.' Agronomy Monograph No. 17, American Society of Agronomy, Madison. pp 433-468.

ROTHERAM, I. (1982). 'Suppression of growth of surrounding regeneration by veteran trees of karri (Eucalyptus diversicolor). Australian Forestry 46:8-13.

SCHOFIELD, N.J., STONEMAN, G.L. and LOH, I.C. (1987). Hydrology of the jarrah forest. In Dell, B., Havel, J.J. and Malajczuk, N. (eds.), 'The Jarrah Book' (in preparation).

SHARMA, M.L., WILLIAMSON, D.R. and HINGSTON, F.J. (1980). Water pollution as a consequence of land disturbance in south-west of Western Australia. In Trudinger, P.A. and Walter, M.R. (eds.), 'Biogeochemistry in ancient and modern environments.' Springer Verlag, Berlin. pp 429-439.

SHARMA, M.L., JOHNSTON, C.D., and BARRON, R.J.W. (1982). Hydrologic responses to forest clearing in a paired catchment study in south-western Australia. In The Institution of Engineers, Australia, 'The first national symposium on forest hydrology.' National Conference Publication No. 82/6. pp 118-123.

SHEA, S.R., HATCH, A.B., HAVEL, J.J. and RITSON, P. (1975). The effect of changes in forest structure and composition on water quality and yields from the northern jarrah forest. In Kikkawa, J. and Nix, H.A. (eds.) 'Managing terrestrial Ecosystems.' Proceedings of the Ecological Society of Australia 9: 58-73.

SMITH, F.G. (1972). 'Vegetation map of Pemberton and Irwin Inlet.' Western Australian Department of Agriculture.

STEERING COMMITTEE (1978). 'Research into the effects of the woodchip industry on water resources in south Western Australia.' (Western Australian) Department of Conservation and Environment, Bulletin No. 31.

STEERING COMMITTEE (1980). 'Research into the effects of the woodchip industry on water resources in south Western Australia.' (Western Australian) Department of Conservation and Environment, Bulletin No. 81.

STOKES, R.A. (1985). 'Stream water and chloride generation in a small forested catchment in south Western Australia.' Water Authority of W.A., Water Resources Directorate, Hydrology Branch Report No. WH7.

STOKES, R.A. and LOH, I.C. (1982). Streamflow and solute characteristics of a forested and deforested catchment pair in south-western Australia. In The Institution of Engineers, Australia, 'The first national symposium on forest hydrology.' National Conference Publication No. 82/6. pp 60-66.

STONEMAN, G.L., ROSE, P. and BORG, H. (1987). 'Forest density response following intensive logging operations in the southern forest of Western Australia'. Department of Conservation and Land Management W.A., Technical Report (in preparation).

STONEMAN, G.L., SCHOFIELD, N.J., and BARTLE, J.R. (1987). Silviculture for water production in the northern jarrah forest : A review. Report of the Forest Management Sub-Committee of the (Western Australian) Steering Committee for Research on Land Use and Water Supply.

TAYLOR, H.M. (1983). Managing root systems for efficient water use : An overview. In Taylor, H.M., Jordan W.R. and Sinclair, T.R. (eds.), 'Limitations to efficient water use in crop production.' American Society of Agronomy, Madison. pp 87-113.

TAYLOR, H.M. and KLEPPER, B. (1978). 'The role of rooting characteristics in the supply of water to plants.' Advances in Agronomy 30:99-128.

TROUSDELL, K.B. and HOOVER, M.D. (1955). 'A change in ground water level after clearcutting of loblolly pine in the Coastal Plain.' Journal of Forestry 53:493-498.

U.S. DEPARTMENT OF THE INTERIOR, BUREAU OF RECLAIMATION (1971). 'Metric supplement to water measurement manual.' United States Government Printing Office, Denver.

WEAVER, J.E. (1920). 'Root development in the grassland formation. A correlation of the root system of native vegetation and crop plants.' Carnegie Institution of Washington, Washington D.C.

WHITE, B.J. and UNDERWOOD, R.J. (1974). 'Regeneration in the karri forest community.' Forests Department of Western Australia.

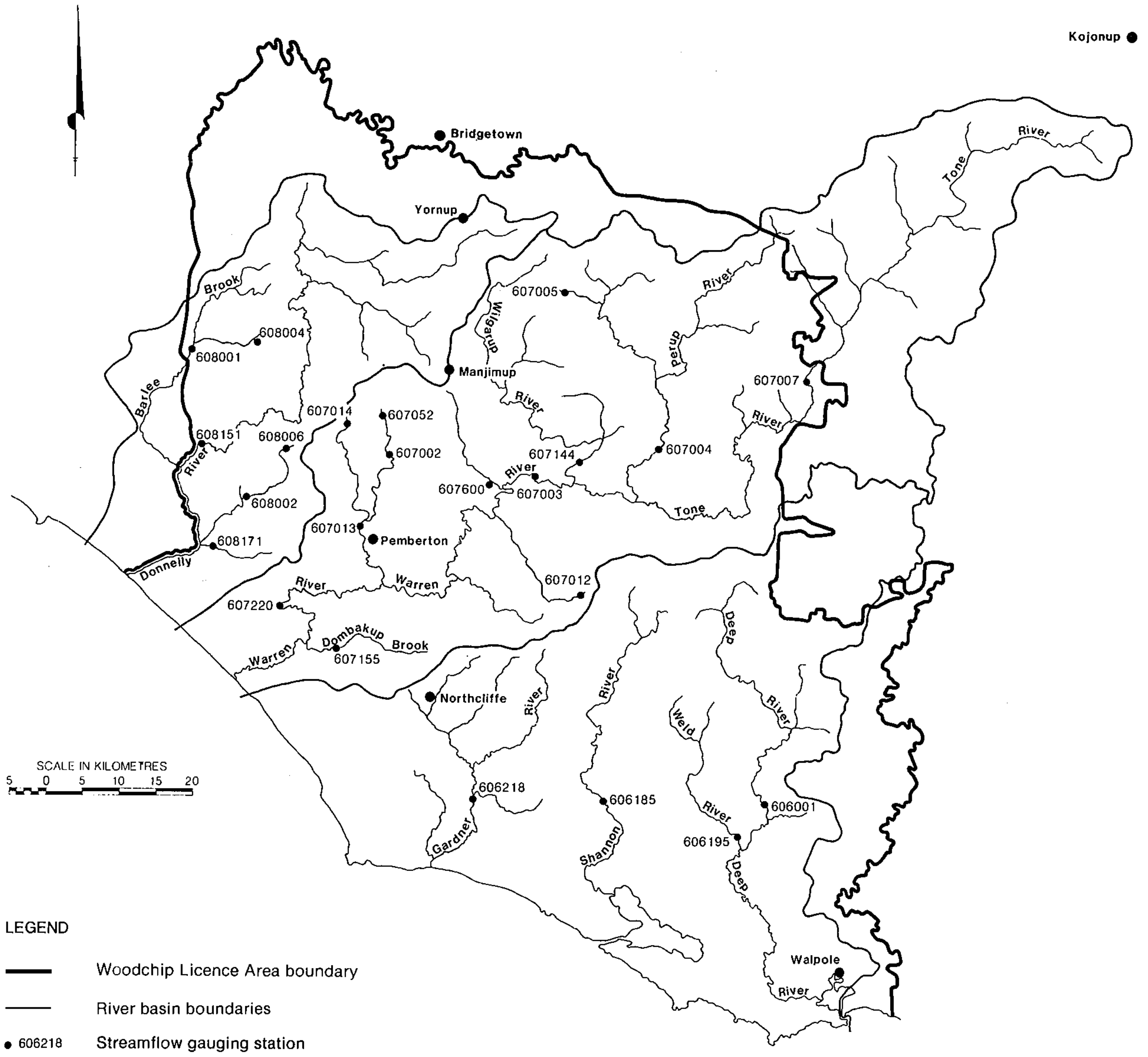
WILDE, S.A., STEINBRENNER, E.C., PIERCE, R.S., DOSEN, R.C., and PRONIN, D.T. (1957). 'Influence of forest cover on the state of the ground water table.' Soil Science Society of America Proceedings 17:65-67.

WILLIAMS, T.M. and LIPSCOMB, D.J. (1981). 'Water table rise after cutting on Coastal Plain soils.' Southern Journal of Applied Forestry 5:46-48.

WILLIAMSON, D.R., STOKES, R.A. and RUPRECHT, J.K. (1987). Responses of catchment water and chloride to experimental clearing for agriculture near Collie, Western Australia. Journal of Hydrology (in press).

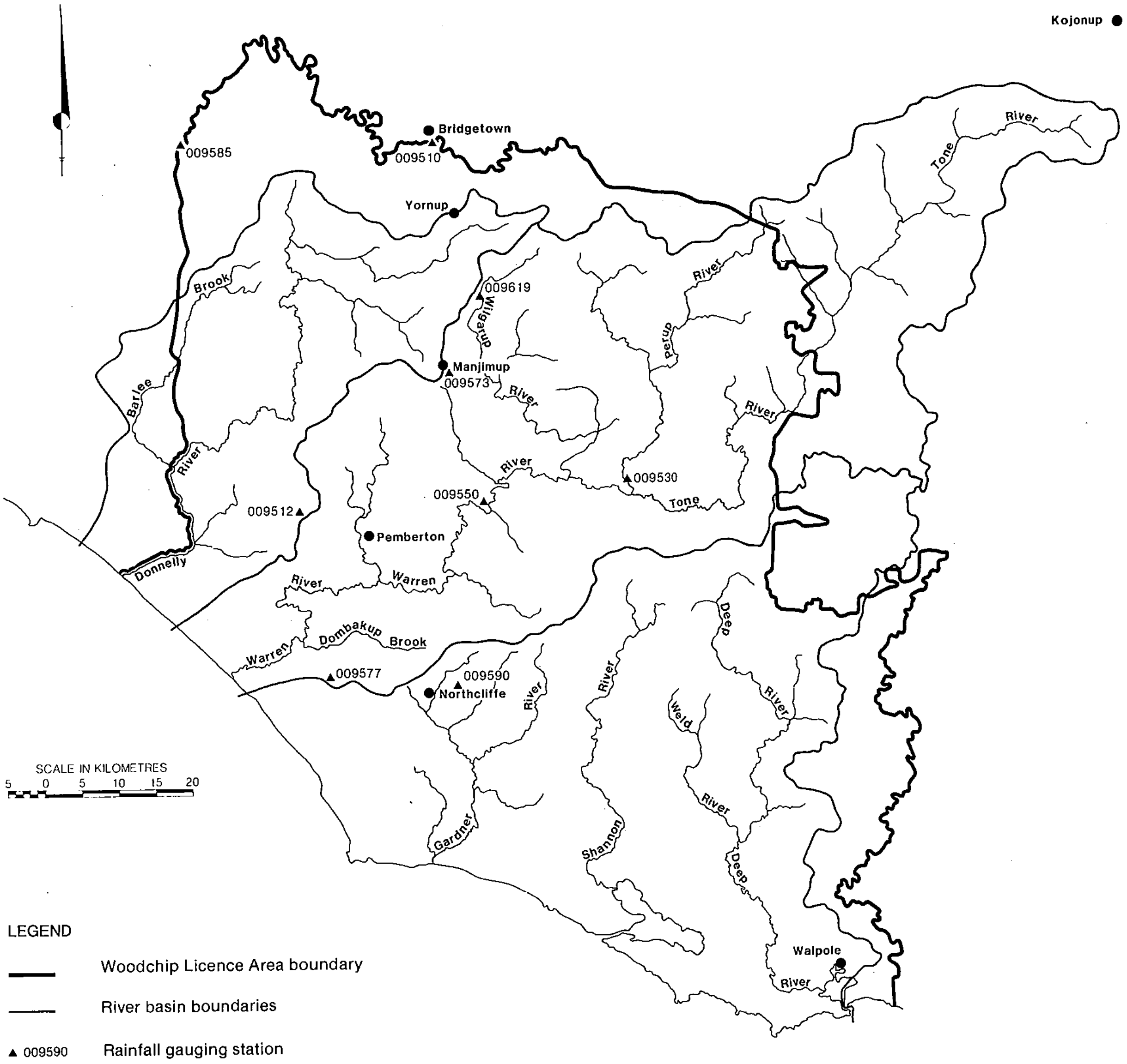
WOOD, W.E. (1924). 'Increase of salt in soil and streams following the destruction of native vegetation.' Journal of the Royal Society of Western Australia 10:35-47.

APPENDICES



Appendix A

Location of the streamflow gauging stations listed in Table 3. (The streamflow gauging stations are operated by the Water Authority of Western Australia.)



Appendix B

Location of the rainfall gauging stations listed in Table 6. (The rainfall gauging stations are operated by the Commonwealth Bureau of Meteorology.)

Appendix C: Annual rainfall in the four research catchments from 1976 to 1985.

Year	Crowea		Poole		Iffley		Mooralup	
	rainfall [mm]	ratio[1]	rainfall [mm]	ratio[1]	rainfall [mm]	ratio[1]	rainfall [mm]	ratio[1]
1976	1 058	.77	1 111	.85	887	.74	691	.79
1977	1 088	.79	993	.76	838	.70	681	.77
1978	1 091	.79	1 019	.78	1 038	.87	766	.87
1979	1 034	.75	939	.72	892	.74	665	.76
1980	1 191	.86	1 099	.84	872	.73	658	.75
1981	1 389	1.01	1 317	1.01	926	.77	821	.93
1982	868	.63	889	.68	735	.61	611	.69
1983	910	.66	981	.75	784	.65	724	.82
1984	1 299	.94	1 216	.93	899	.75	771	.88
1985	1 079	.78	1 121	.86	739	.62	587	.67
mean for 1976 through 1985	1 101	.80	1 069	.82	861	.72	698	.79
mean for 1926 through 1976[2]	1 380	1.00	1 310	1.00	1 200	1.00	880	1.00

[1] ratio between the rainfall in the respective year and the mean annual rainfall for 1926 through 1976

[2] estimated from Figure 2

Appendix D: Annual streamflow in the four research catchments from 1976 to 1985.

	Crowea		Poole		Iffley		Mooralup	
	streamflow		streamflow		streamflow		streamflow	
Year	[mm]	[% of rainfall]	[mm]	[% of rainfall]	[mm]	[% of rainfall]	[mm]	[% of rainfall]
1976	128	12.1	51	4.6	91	10.3	6	.9
1977	240	22.1	89	9.0	137	16.3	4	.7
1978	420	38.5	347	34.1	315	30.3	31	4.0
1979	295	28.5	226	24.1	193	21.6	.5	.1
1980	295	24.7	293	26.7	271	31.1	5	.8
1981	439	31.6	416	31.6	290	31.3	27	3.3
1982	223	25.7	151	16.9	225	30.6	no flow	
1983	243	26.7	145	14.8	167	21.3	11	1.5
1984	284	21.8	197	16.2	205	22.8	6	.8
1985	167	15.4	117	10.4	142	19.2	no flow	

Appendix E: Periods of streamflow in the four research catchments from 1976 to 1985.

Year	Crowea flow period [day.month]	Poole flow period [day.month]	Iffley flow period [day.month]	Mooralup flow period [day.month]
1976	3.5 to 2.2.1977	23.7 to 17.11	23.6 to 29.11	8.8 to 15.12
1977	11.5 to	22.7 to 17.11	15.6 to 2.12	8.8 to 7.12
1978		26.5 to 4.12	21.5 to 25.12	29.6 to 22.11
1979		20.5 to 29.11	16.5 to 15.1.1980	25.9 to 27.11
1980		21.5 to 27.11	15.4 to 30.12	6.8 to 30.11
1981		29.5 to 7.12	4.5 to 22.12	26.7 to 26.11
1982		7.6 to 8.11	24.5 to 24.11	no flow
1983		25.6 to 18.10	22.6 to 18.11	29.8 to 11.11
1984		5.6 to 1.12	26.5 to 30.11	10.8 to 4.12
1985	↓ continuous	19.7 to 15.10	6.6 to 26.11	no flow

Appendix F: Stream salinity in the four research catchments from 1976 to 1985.

Year	Crowea			Poole			Iffley			Mooralup		
	stream salinity [mg/L TSS]			stream salinity [mg/L TSS]			stream salinity [mg/L TSS]			stream salinity [mg/L TSS]		
	min.	max.	mean[1]	min	max	mean[1]	min	max	mean[1]	min	max	mean[1]
1976	96	272	142	96	128	102	264	631	352	no data		
1977	105	247	142	105	128	112	273	534	316	126	145	138
1978	97	309	164	108	186	145	151	775	276	93	112	105
1979	126	304	192	126	216	196	265	806	432	121	166	137
1980	102	314	179	138	265	189	297	846	428	133	138	142
1981	71	264	131	93	206	138	180	682	285	65	108	81
1982	127	332	179	160	231	189	230	602	376	no flow		
1983	88	307	184	122	196	167	191	282	324	65	167	84
1984	91	194	141	101	186	145	175	499	216	71	148	81
1985	88	283	153	130	162	163	156	583	307	no flow		

[1] flow-weighted

Appendix G: Minimum annual water level averaged for control bores and catchment bores in the four research catchments from 1975 to 1986, given as depth below soil surface [m].

Year	Crowea				Poole				Iffley				Mooralup			
	control bores	catch-ment bores	Δh_1	Δh_2	control bores	catch-ment bores	Δh_1	Δh_2	control bores	catch-ment bores	Δh_1	Δh_2	control bores	catch-ment bores	Δh_1	Δh_2
1975	10.61	6.54	.40	.19	5.85	8.95	.23	-.03	9.96	8.57	.24	.10	dry	8.79	-.48	
1976	10.82	6.94	0.00	0.00	6.11	9.18	0.00	0.00	10.10	8.81	0.00	0.00	dry	8.31	0.00	
1977	11.23	6.51	.43	.84	6.65	9.53	-.35	.19	10.71	9.08	-.27	.34	dry	8.36	-.05	
1978	11.45	4.87	2.07	2.70	7.25	6.80	2.38	3.52	11.27	8.50	.31	1.48	dry	8.16	.15	
1979	11.57	4.15	2.79	3.54	6.23	4.09	5.09	5.21	11.34	7.57	1.24	2.48	dry	7.54	.77	
1980	11.64	4.18	2.76	3.58	6.43	3.81	5.37	5.69	11.65	7.29	1.52	3.07	dry	7.52	.79	
1981	10.81	4.27	2.67	2.66	5.93	3.75	5.43	5.25	11.63	7.04	1.77	3.30	dry	7.48	.83	
1982	9.91	4.45	2.49	1.58	5.44	4.09	5.09	4.42	11.33	7.14	1.67	2.90	dry	7.18	1.13	
1983	11.11	5.03	1.91	2.20	6.88	5.74	3.44	4.21	11.84	7.81	1.00	2.74	dry	7.54	.77	
1984	11.96	5.51	1.43	2.57	7.40	6.66	2.52	3.81	12.05	8.19	.62	2.57	dry	7.56	.75	
1985	11.36	5.41	1.53	2.07	6.51	6.51	2.67	3.07	12.21	8.37	.44	2.55	dry	7.46	.85	
1986	11.46	5.72	1.22	1.86	6.55	7.00	2.18	2.62	12.61	8.76	.05	2.56	dry	7.51	.80	

Δh_1 = 1976 water level in catchment bores - water level in catchment bores in year X.

Δh_2 = (year X water level in control bores - year X water level in catchment bores) - (1976 water level in control bores - 1976 water level in catchment bores).

Appendix H: Minimum annual water level in each bore in the four research catchments from 1975 to 1986. (Plus signs indicate the height of the water level above the soil surface, all other values indicate the distance of the water level below the soil surface. Different line types in the graphs were chosen for clarity.)

CROWEA

	bore number[1]											
Year	13	14	15	16	17	18	19	20	21	22	23	24
1975	dry	1.56	10.01	dry	7.61	5.21	dry	15.76	.11	14.76	17.16	4.06
1976	dry	1.86	10.66	dry	7.81	5.66	dry	16.61	.51	15.16	17.38	4.26
1977	dry	1.24	10.46	dry	7.31	4.64	dry	dry	.08	15.31	17.90	4.55
1978	dry	.08	8.23	dry	5.74	1.91	dry	dry	+.79	14.04	18.13	4.76
1979	dry	.10	7.06	dry	5.31	1.20	7.01	12.26	+.82	12.06	18.36	4.78
1980	dry	.16	7.21	13.09	5.26	1.41	7.11	12.18	+.19	11.21	18.51	4.77
1981	13.61	.46	7.41	12.26	5.23	1.49	7.13	12.28	.16	10.86	17.66	3.96
1982	14.21	.93	7.36	12.16	5.41	1.84	7.01	12.66	.47	10.66	16.26	3.56
1983	dry	1.21	8.41	13.11	5.91	2.71	8.71	dry	+.04	11.96	17.66	4.56
1984	dry	1.46	8.96	13.61	6.36	3.56	dry	15.11	+.04	12.76	18.81	5.11
1985	dry	1.31	8.86	13.86	6.16	3.21	dry	16.51	+.04	13.06	18.41	4.30
1986	dry	1.76	9.46	14.06	6.41	3.63	dry	dry	+.09	13.17	18.71	4.21
depth to bottom of bore [m]	17.90	21.29	18.36	14.32	13.47	20.96	9.69	17.49	14.86	23.98	22.51	16.39
elevation at bore [m]	126.95	95.95	109.05	127.24	112.22	110.05	127.72	140.86	116.55	136.41	111.47	95.17
AWRC I.D. number	6078610	6078611	6078612	6078604	6078607	6078614	6078613	6078601	6078615	6078616	6078617	6078620

[1] bores 13 to 22 are catchment bores, bore 23 and 24 are control bores

POOLE

	bore number[1]											
Year	25	26	27	28	29	30	31	32	33	34	35	36
1975	dry	3.36	3.46	10.26	dry	10.46	10.06	12.93	14.56	6.51	4.19	7.51
1976	dry	4.76	3.46	9.96	dry	10.31	10.06	13.04	14.97	6.86	4.56	7.66
1977	dry	5.02	4.27	10.38	dry	10.26	9.96	13.01	15.68	7.65	5.03	8.26
1978	dry	3.66	1.64	6.41	dry	7.82	6.37	12.18	12.06	4.25	5.56	8.93
1979	dry	.69	1.00	4.00	dry	6.02	3.72	7.46	8.49	1.35	4.61	7.84
1980	dry	1.04	.86	3.86	dry	5.65	3.16	6.08	8.27	1.56	4.86	8.00
1981	dry	.89	.74	4.26	dry	5.32	3.14	5.71	8.48	1.46	4.24	7.61
1982	dry	1.10	.86	4.18	dry	5.26	3.61	6.49	9.28	1.96	3.86	7.01
1983	dry	1.76	1.76	6.41	dry	6.36	5.61	8.61	11.38	4.06	5.16	8.59
1984	dry	2.56	1.61	7.26	dry	7.06	7.21	9.80	12.76	5.04	5.68	9.11
1985	dry	1.63	1.21	7.06	dry	6.81	7.11	10.31	12.96	4.96	4.86	8.16
1986	dry	1.36	1.16	7.51	dry	7.41	8.16	11.41	13.46	5.51	4.83	8.26
depth to bottom of bore [m]	4.79	8.55	10.08	11.32	8.90	10.40	10.05	13.11	33.93	22.82	32.95	18.64
elevation at bore [m]	191.16	162.70	161.76	168.57	199.76	182.00	178.03	183.44	187.86	180.29	160.75	164.58
AWRC I.D. number	6078704	6078705	6078706	6078707	6078703	6078716	6078713	6078710	6078701	6078702	6078717	6078720

---

[1] bores 25 to 34 are catchment bores, bore 35 and 36 are control bores

IFFLEY

Year	bore number[1] 1	2	3	4	5	6	7	8	9	10	11	12
1975	dry	2.73	14.96	17.28	.94	14.76	12.76	+.34	+.50	14.56	14.46	5.46
1976	dry	2.76	14.99	17.66	1.16	14.56	14.02	+.34	+.50	15.01	14.74	5.46
1977	dry	2.94	16.52	17.61	1.28	15.22	14.58	+.34	+1.35	15.30	15.50	5.91
1978	dry	2.26	14.87	16.92	1.16	14.96	13.43	+.36	+1.85	15.10	16.11	6.42
1979	dry	1.45	12.86	15.15	.76	12.97	12.96	+.34	+2.01	14.34	16.38	6.30
1980	dry	1.26	12.56	15.96	.71	12.56	11.14	+.59	+2.02	14.00	16.59	6.71
1981	dry	1.29	12.01	15.51	.54	12.71	10.62	+.94	+2.10	13.75	16.49	6.76
1982	dry	1.31	11.78	16.38	.64	12.37	10.93	+.79	+2.00	13.66	16.09	6.56
1983	dry	1.86	13.26	17.51	.84	13.36	11.74	+.84	+2.00	14.56	16.51	7.16
1984	dry	2.24	13.93	17.51	1.01	13.86	11.96	+.84	+1.80	15.86	16.84	7.26
1985	dry	2.46	14.48	17.46	.96	14.16	11.90	+.74	+1.70	16.31	17.16	7.26
1986	dry	2.81	15.26	17.61	.98	14.66	12.46	+.14	+1.49	16.66	17.56	7.66
depth to bottom of bore [m]	20.98	13.22	18.00	17.95	6.52	18.07	31.03	18.20	25.60	11.84	25.66	25.55
elevation at bore [m]	95.80	112.94	137.87	149.21	108.88	127.74	159.68	150.51	142.49	132.47	154.65	181.62
AWRC I.D. number	6088201	6088212	6088209	6088217	6088208	6088207	6088215	6088205	6088216	6088206	6088202	6088219

---

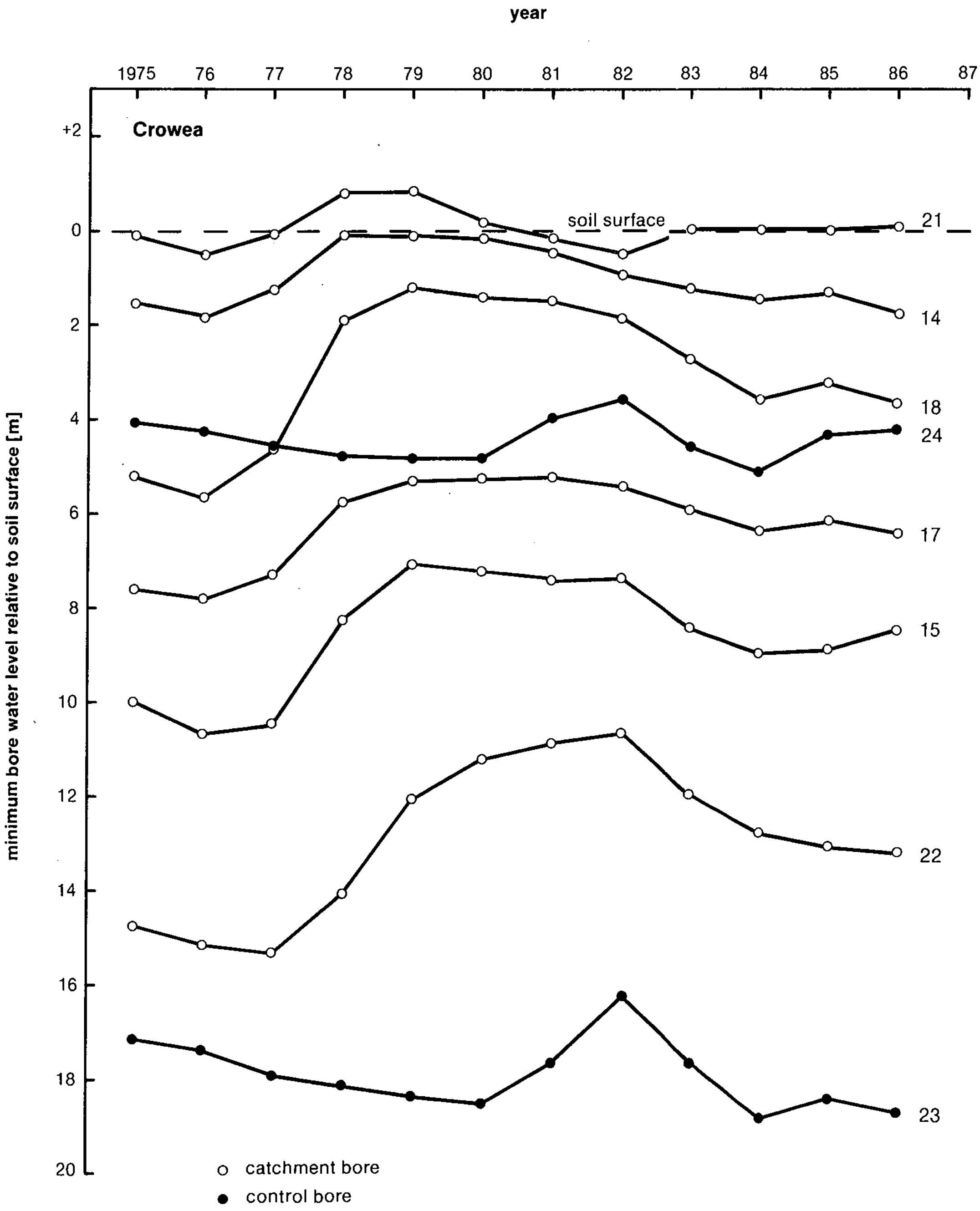
[1] bores 1 to 10 are catchment bores, bore 11 and 12 are control bores

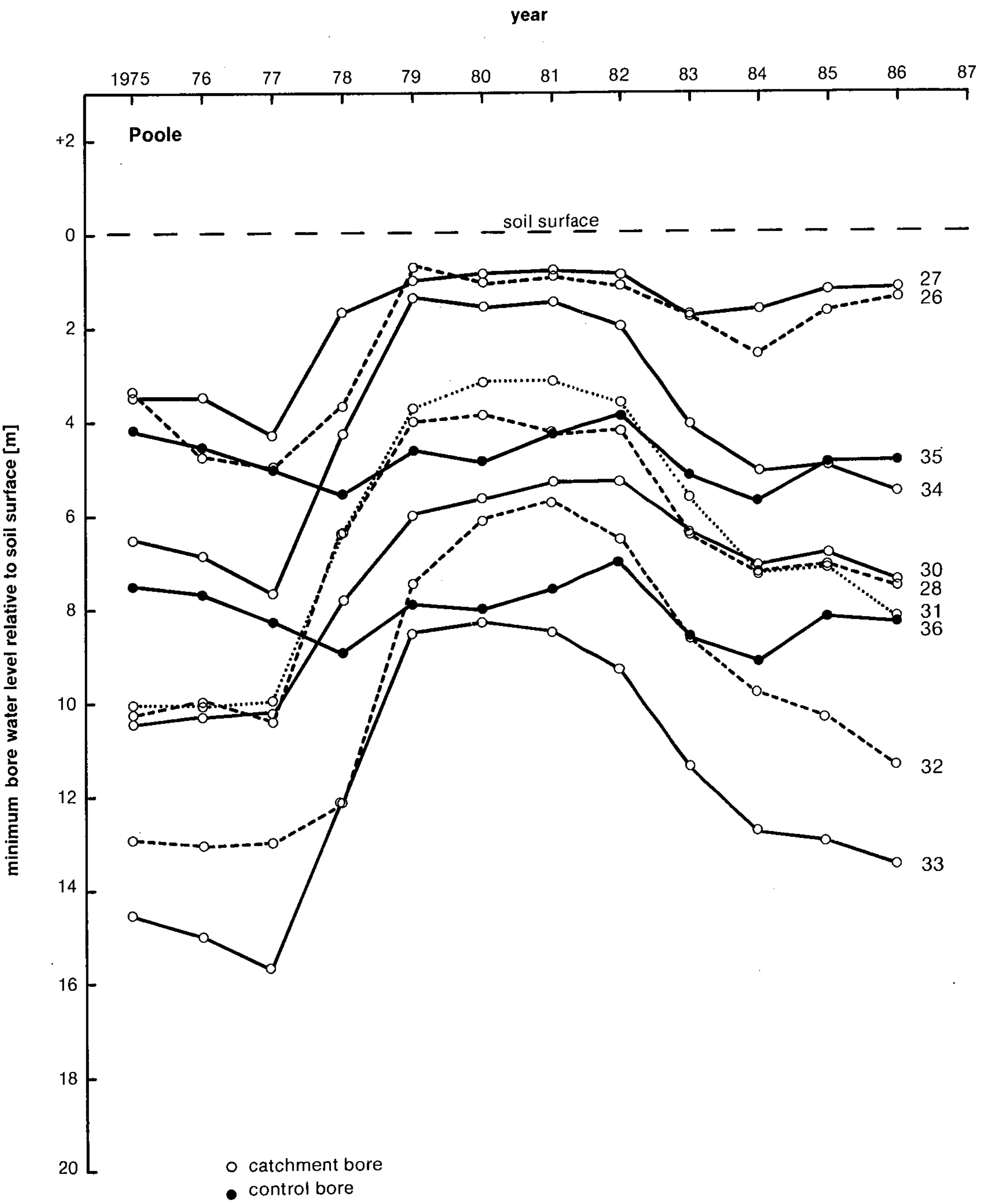
MOORALUP

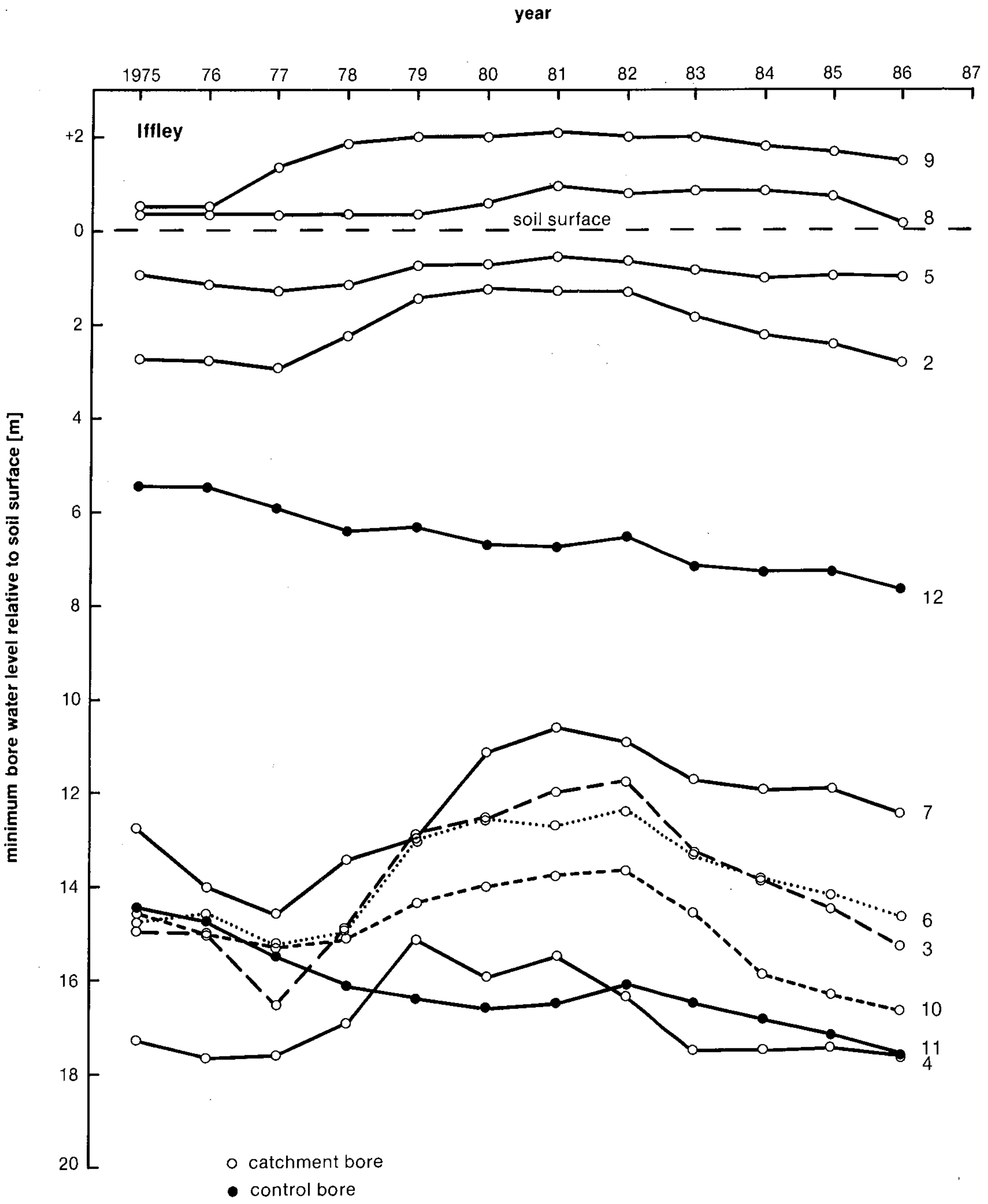
Year	bore number[1] 37	38	39	40	41	42	43	44	45	46	47	48
1975	dry	8.79	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1976	dry	8.31	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1977	dry	8.36	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1978	dry	8.16	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1979	dry	7.54	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1980	dry	7.52	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1981	dry	7.48	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1982	dry	7.18	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1983	dry	7.54	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1984	dry	7.56	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1985	dry	7.46	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
1986	dry	7.51	dry	dry	dry	dry	dry	dry	dry	dry	dry	dry
depth to bottom of bore [m]	17.83	9.96	15.96	20.27	6.20	16.34	20.70	13.42	10.46	18.39	21.77	10.07
elevation at bore [m]	171.01	151.91	160.65	191.25	173.02	171.73	188.03	200.46	196.12	198.88	187.20	194.39
AWRC I.D. number	6078514	6078515	6078516	6078504	6078505	6078508	6078511	6078501	6078502	6078503	6078519	6078520

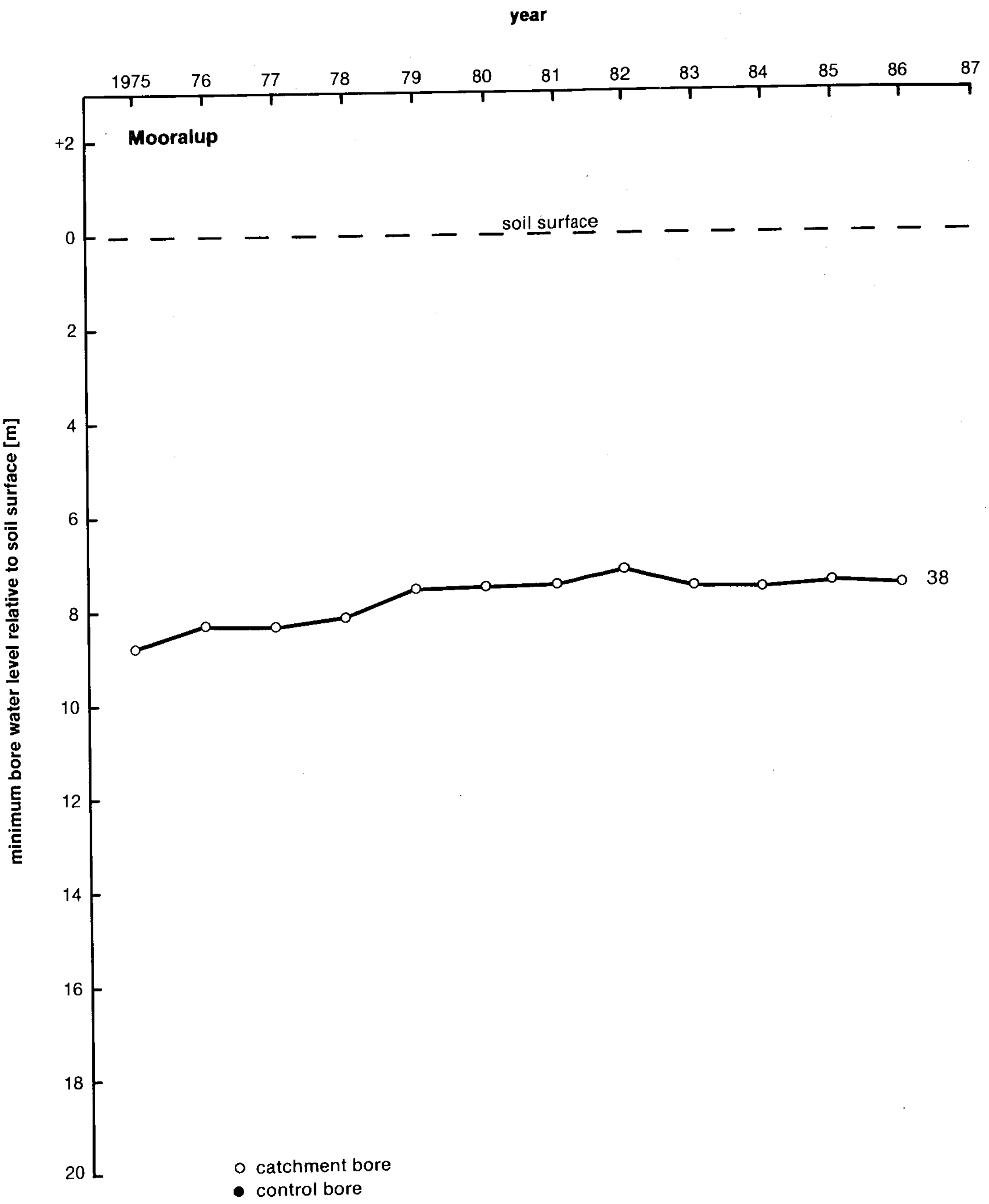
---

[1] bores 37 to 46 are catchment bores, bore 47 and 48 are control bores

year
1975
76
77
78
79
80
81
82
83
84
85
86
87
+2
0
2
4
6
8
10
12
14
16
18
20
minimum bore water level relative to soil surface [m]
Crowea
soil surface
21
14
18
24
17
15
22
23
○ catchment bore
● control bore


year
1975
76
77
78
79
80
81
82
83
84
85
86
87
Poole
soil surface
minimum bore water level relative to soil surface [m]
+2
0
2
4
6
8
10
12
14
16
18
20
27
26
35
34
30
28
31
36
32
33
○ catchment bore
● control bore


year
1975
76
77
78
79
80
81
82
83
84
85
86
87
Iffley
+2
0
2
4
6
8
10
12
14
16
18
20
soil surface
minimum bore water level relative to soil surface [m]
9
8
5
2
12
7
6
3
10
11
4
○ catchment bore
● control bore


year
1975
76
77
78
79
80
81
82
83
84
85
86
87
Mooralup
soil surface
+2
0
2
4
6
8
10
12
14
16
18
20
minimum bore water level relative to soil surface [m]
38
○ catchment bore
● control bore

Appendix I: Maximum and minimum annual salinity (mg/L TSS) in each bore in the four research catchments from 1975 to 1986.

CROWEA

	13		14		15		16		17		18		19		20		21		22		23		24	
Year	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.
1975	dry		586	276	143	111	803	558	379	61	983	384	dry		240	187	815	724	385	321	286	223	318	79
1976	dry		373	258	136	116	872	258	273	239	768	320	dry		260	186	812	260	351	320	258	84	410	82
1977	dry		283	260	146	112	dry		371	208	864	294	dry		251	225	740	549	349	324	278	209	304	55
1978	dry		288	250	181	112	dry		272	105	542	254	221	169	213	136	640	552	369	325	276	226	339	58
1979	dry		314	242	140	112	2827	702	495	114	396	163	387	157	326	118	605	112	343	217	343	223	343	64
1980	dry		302	243	264	106	3111	645	443	74	367	302	381	246	281	131	511	463	299	249	275	223	251	52
1981	990	666	595	250	221	124	221	124	522	116	508	328	396	118	356	187	752	454	396	253	413	164	307	108
1982	1213	717	444	388	319	178	3700	306	570	154	603	403	481	253	456	236	961	298	608	346	739	219	491	138
1983	1248	1091	476	345	299	189	4492	293	496	148	895	310	486	312	547	331	1129	716	552	369	443	275	377	117
1984	dry		401	322	294	185	5037	113	581	107	630	164	445	315	367	190	864	695	832	136	522	156	393	103
1985	dry		391	315	240	145	4783	2119	549	113	801	291	439	424	492	224	859	665	558	317	437	246	283	114
1986	dry		209	154	209	154	4381	3077	1356	425	494	357	dry		353	246	720	570	369	dry	356	300	294	172

POOLE

Year	25 max.	25 min.	26 max.	26 min.	27 max.	27 min.	28 max.	28 min.	29 max.	29 min.	30 max.	30 min.	31 max.	31 min.	32 max.	32 min.	33 max.	33 min.	34 max.	34 min.	35 max.	35 min.	36 max.	36 min.
1975		dry	1302	372	1176	96	655	373		dry	1806	234	1693	958	2519	2272	868	177	370	291	545	105	652	249
1976		dry	751	308	218	116	838	261		dry	859	329	1595	267	2371	2080	336	173	331	290	351	85	572	260
1977		dry	483	129	225	99	426	167		dry	589	250	868	192	2051	583	314	173	484	206	389	62	389	62
1978		dry	223	142	305	130	361	59		dry	505	174	1048	182	1696	84	258	135	322	139	413	70	413	70
1979		dry	224	167	342	265	152	87		dry	346	98	1472	206	2094	692	502	114	373	236	331	53	331	53
1980		dry	250	178	338	196	326	32		dry	333	113	2082	100	3176	123	294	86	469	266	319	58	319	58
1981		dry	320	177	658	294	219	103	97	dry	1015	294	3427	141	2996	132	608	140	3295	246	545	100	840	255
1982		dry	357	55	563	315	510	136		dry	2030	1011	4779	217	3362	286	489	164	492	357	474	146	442	342
1983		dry	750	288	549	453	412	129		dry	1834	298	5333	193	5186	194	687	270	687	270	676	151	411	325
1984		dry	565	285	543	417	422	92	215	161	1853	345	3169	219	3406	105	426	139	619	241	497	137	692	313
1985		dry	410	259	566	412	688	164		dry	1788	359	1518	304	3069	189	383	127	468	214	458	127	58	293
1986		dry	286	241	459	369	693	230		dry	1073	777	853	476	2437	1686	237	169	364	298	408	330	354	274

IFFLEY

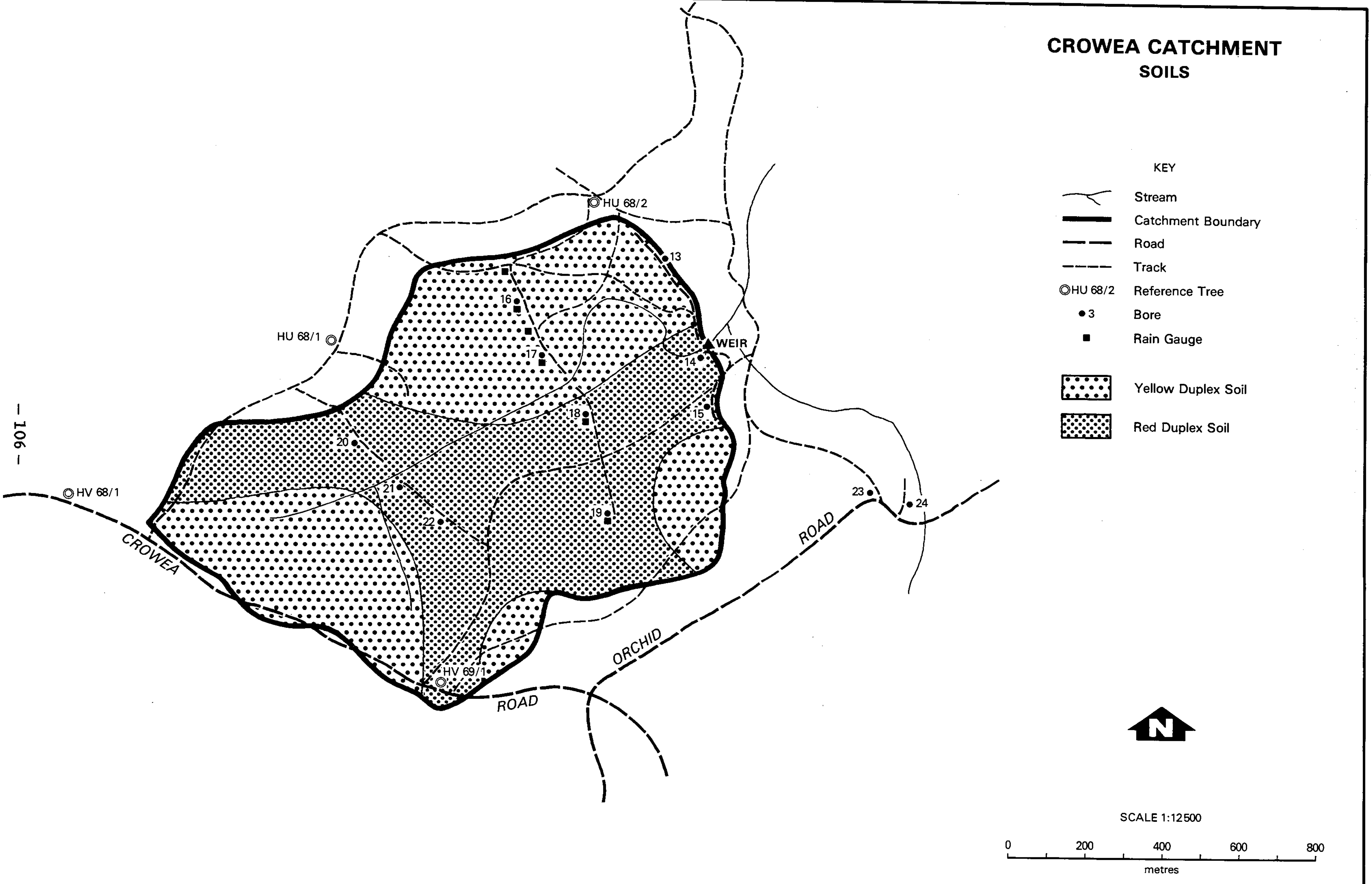
	1		2		3		4		5		6		7		8		9		10		11		12	
Year	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.
1975	dry		500	241	1080	989	824	148	600	395	1736	1150	1957	91	530	490	651	603	1529	612	776	38	2585	131
1976	dry		384	228	1084	921	1134	266	752	411	1572	1359	5081	306	554	464	667	583	1356	1009	510	89	687	150
1977	dry		366	210	1098	843	771	275	817	394	1536	512	3188	110	1514	486	655	589	1221	959	1421	24	393	157
1978	dry		302	115	1093	972	395	69	566	444	1560	1297	1656	49	616	462	616	462	1184	124	710	35	269	136
1979	dry		338	257	1113	875	724	67	594	463	1502	1234	767	71	531	463	708	463	768	163	537	27	409	143
1980	dry		302	257	1101	1010	149	56	531	476	1444	1151	417	51	526	442	526	443	1113	110	537	18	307	131
1981	dry		437	299	1490	971	176	98	757	464	1906	1266	1734	105	738	415	860	493	832	284	696	79	186	97
1982	dry		543	379	1668	1268	1668	155	850	649	2370	1790	1912	120	831	629	876	690	1527	244	832	93	294	138
1983	dry		490	312	1414	1013	425	132	765	678	2160	206	1794	116	749	655	824	704	1981	272	773	95	232	137
1984	dry		509	367	1378	976	366	136	813	564	2152	1649	1162	100	785	608	879	668	3269	253	797	81	252	103
1985	dry		523	384	1128	849	421	138	760	617	760	617	1271	122	765	610	884	713	531	213	781	117	239	117
1986	dry		442	352	954	671	278	dry	733	572	2099	1600	1146	348	758	581	852	756	798	337	807	338	165	100

MOORALUP

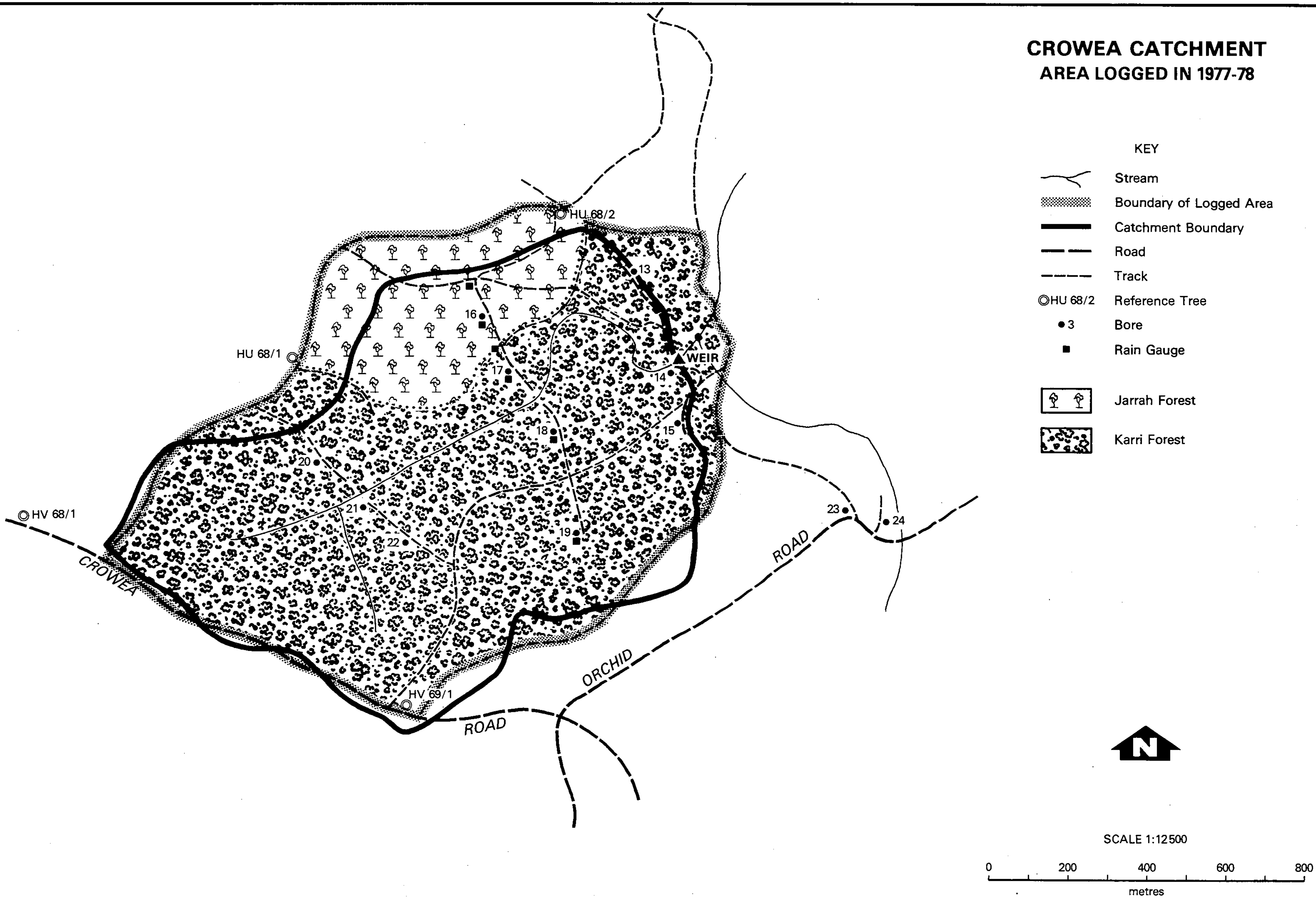
Year	37		38		39		40		41		42		43		44		45		46		47		48	
	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.
1975	dry		9768	8934	dry		dry		dry		dry		dry		dry		dry		dry		dry		600	261
1976	dry		9398	2986	dry		dry		dry		dry		dry		dry		dry		dry		dry		dry	
1977	2929	dry	8791	2808	dry		dry		dry		dry		dry		dry		dry		dry		dry		dry	
1978	dry		8205	100	dry		dry		202	149	dry		1405	889	dry		1248	946	283	103	dry		272	111
1979	dry		6591	613	dry		dry		dry		dry		dry		dry		1333	776	dry		dry		206	131
1980	949	dry	8956	1069	dry		105	dry	105	dry	dry		dry		dry		dry		114	dry	dry		233	98
1981	dry		12472	131	dry		218	dry	331	257	351	151	977	849	dry		743	457	dry		dry		274	162
1982	dry		12440	895	dry		dry		dry		dry		dry		dry		dry		dry		dry		dry	
1983	dry		11979	127	dry		dry		dry		dry		1257	817	dry		dry		dry		dry		180	dry
1984	dry		7039	147	dry		dry		dry		1035	dry	1539	961	dry		483	478	dry		dry		176	161
1985	dry		9896	167	dry		dry		dry		663	dry	1121	dry	dry		402	dry	dry		dry		165	dry
1986	dry		9540	7572	dry		dry		dry		dry		dry		dry		dry		dry		dry		dry	

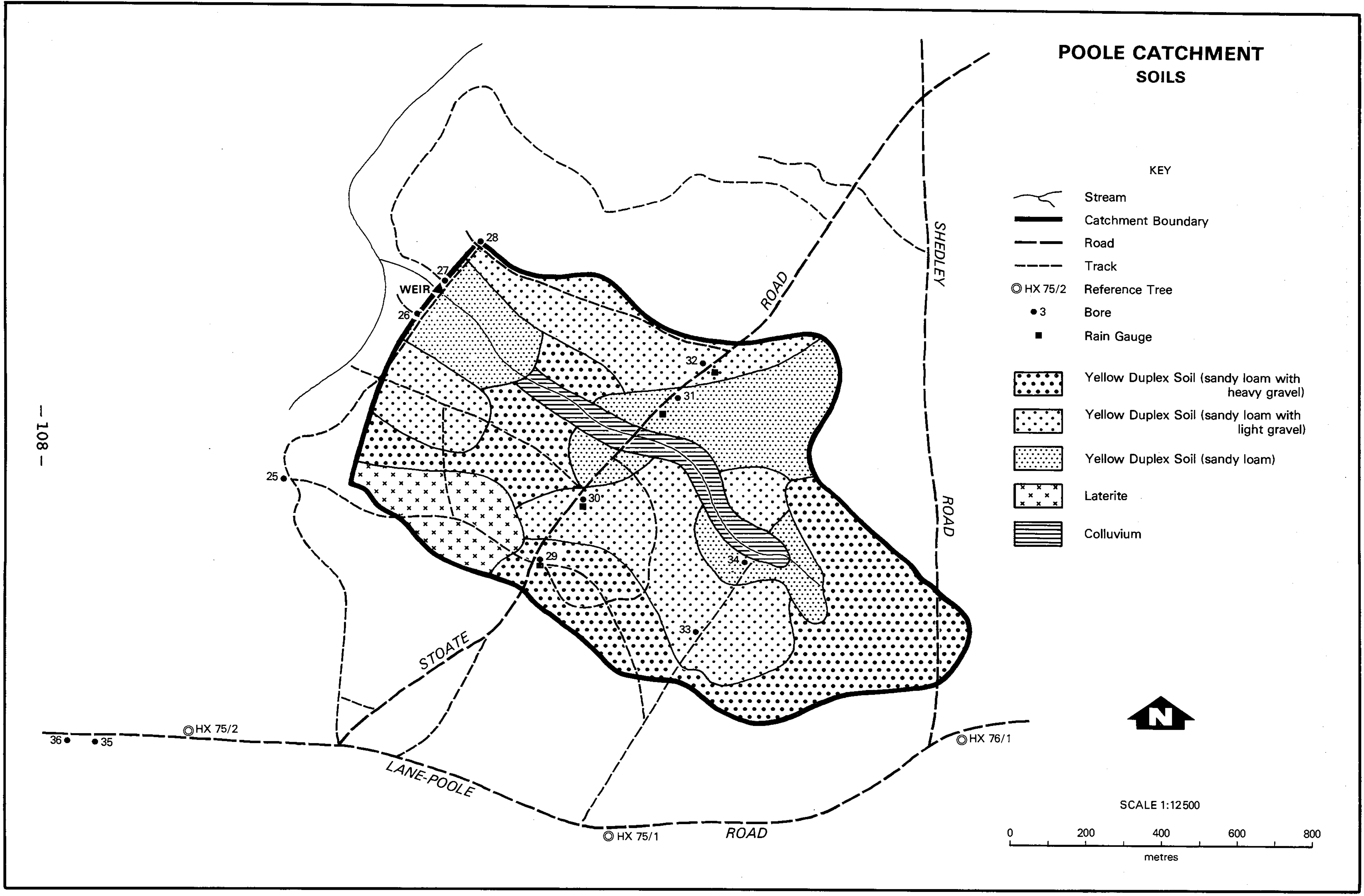
Appendix J: Distribution of soil types and areas logged in the four research catchments.

CROWEA CATCHMENT
SOILS



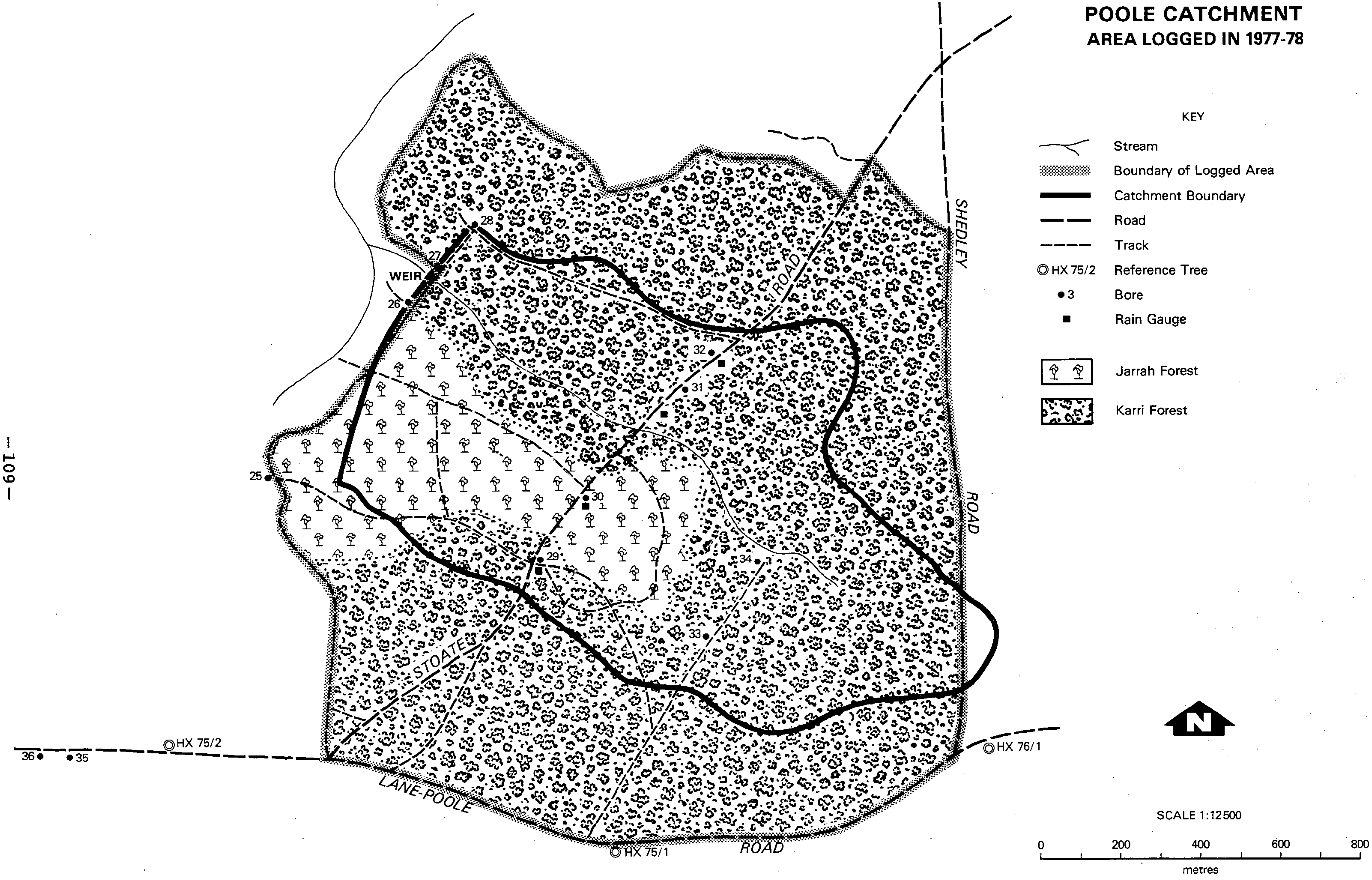
CROWEA CATCHMENT
AREA LOGGED IN 1977-78



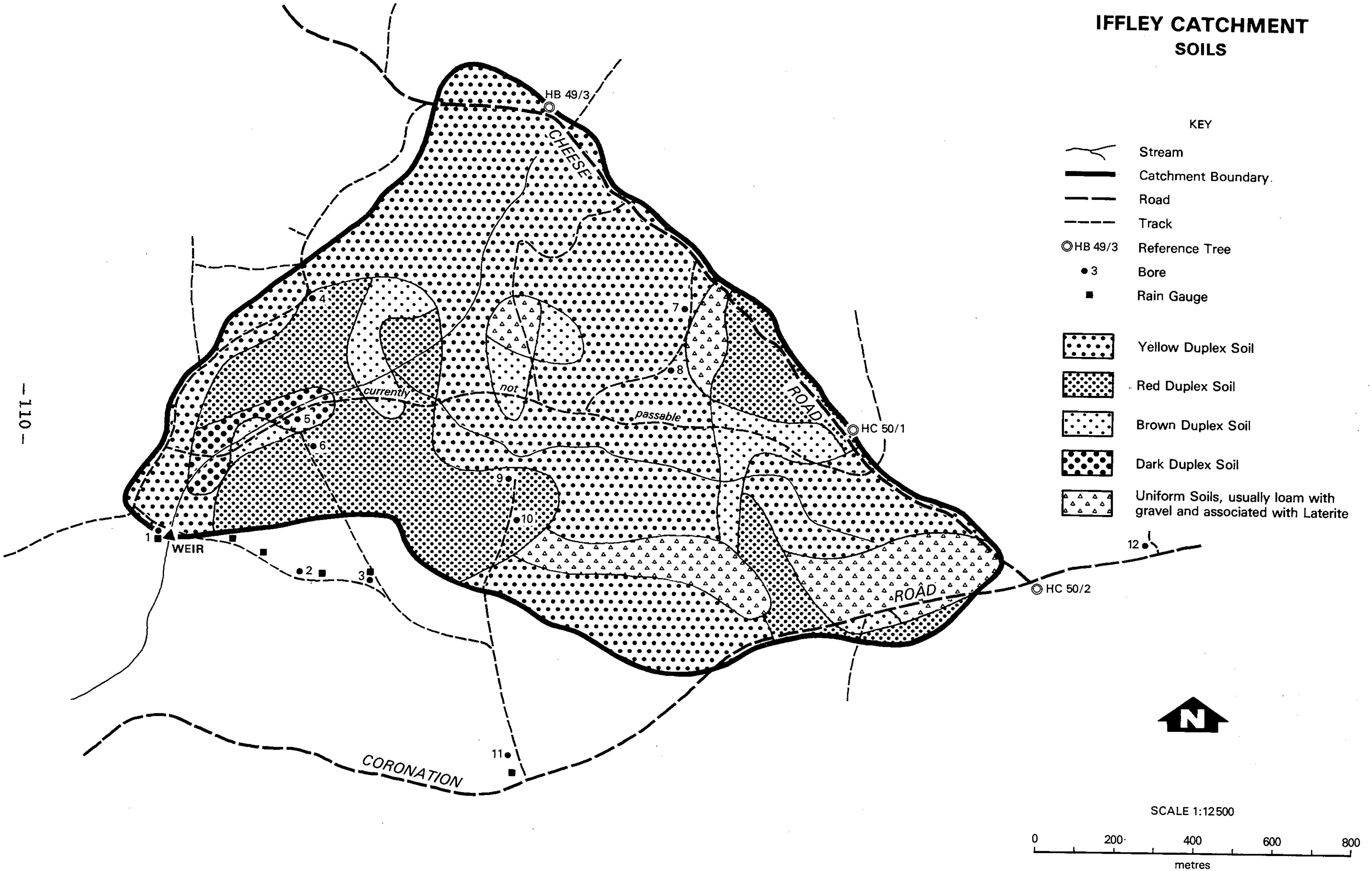


POOLE CATCHMENT
SOILS

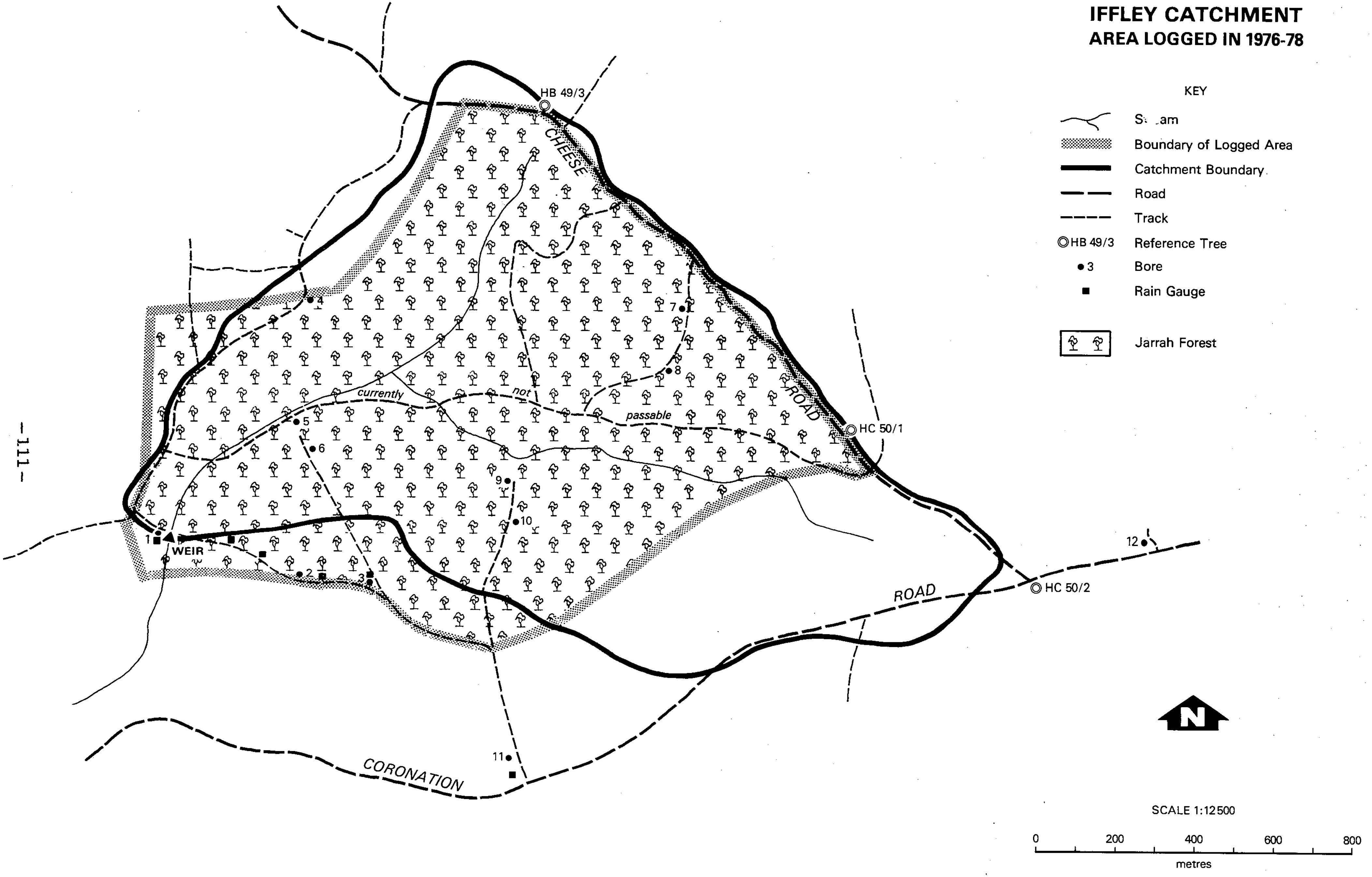
POOLE CATCHMENT
AREA LOGGED IN 1977-78



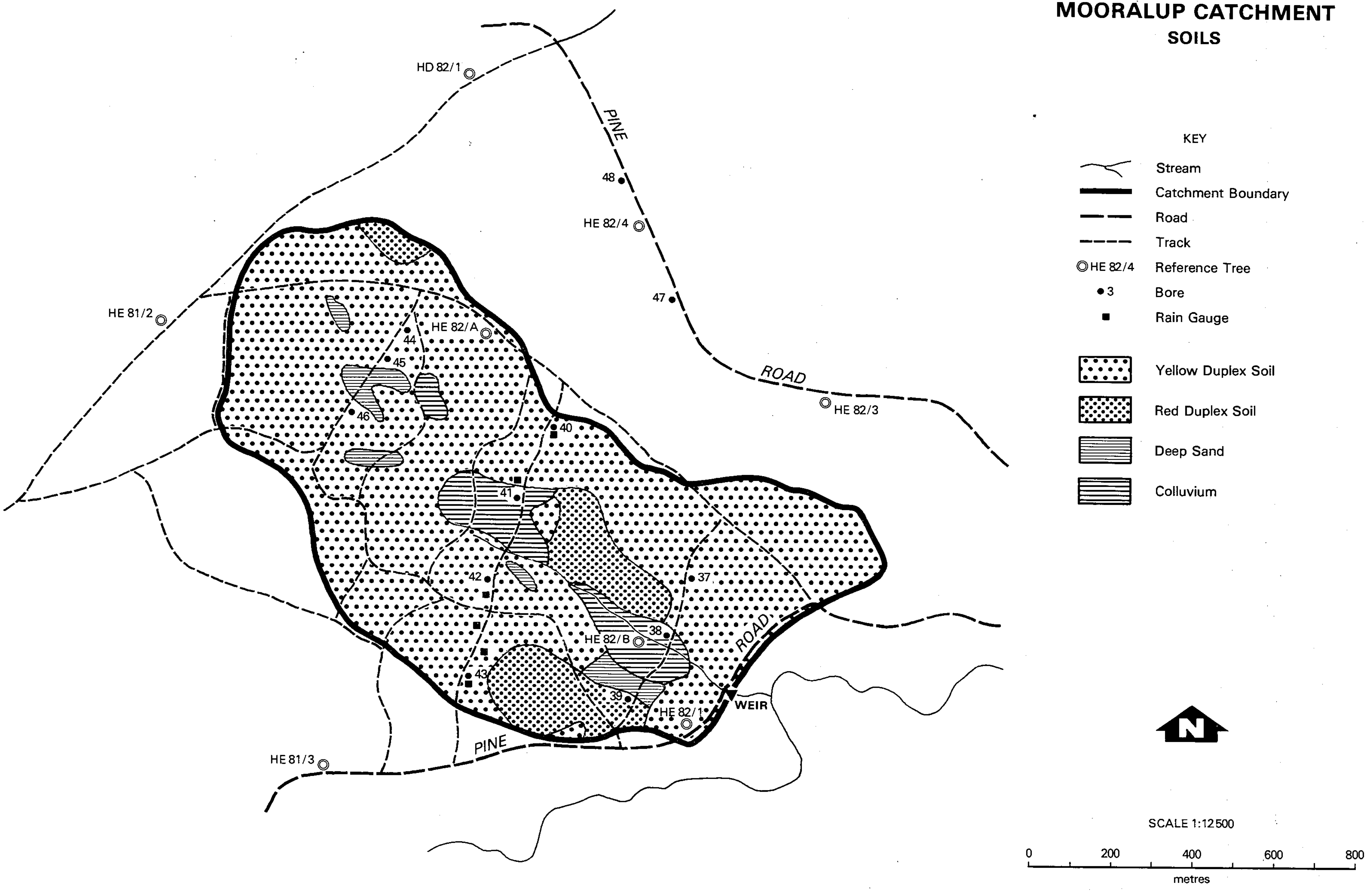
IFFLEY CATCHMENT
SOILS



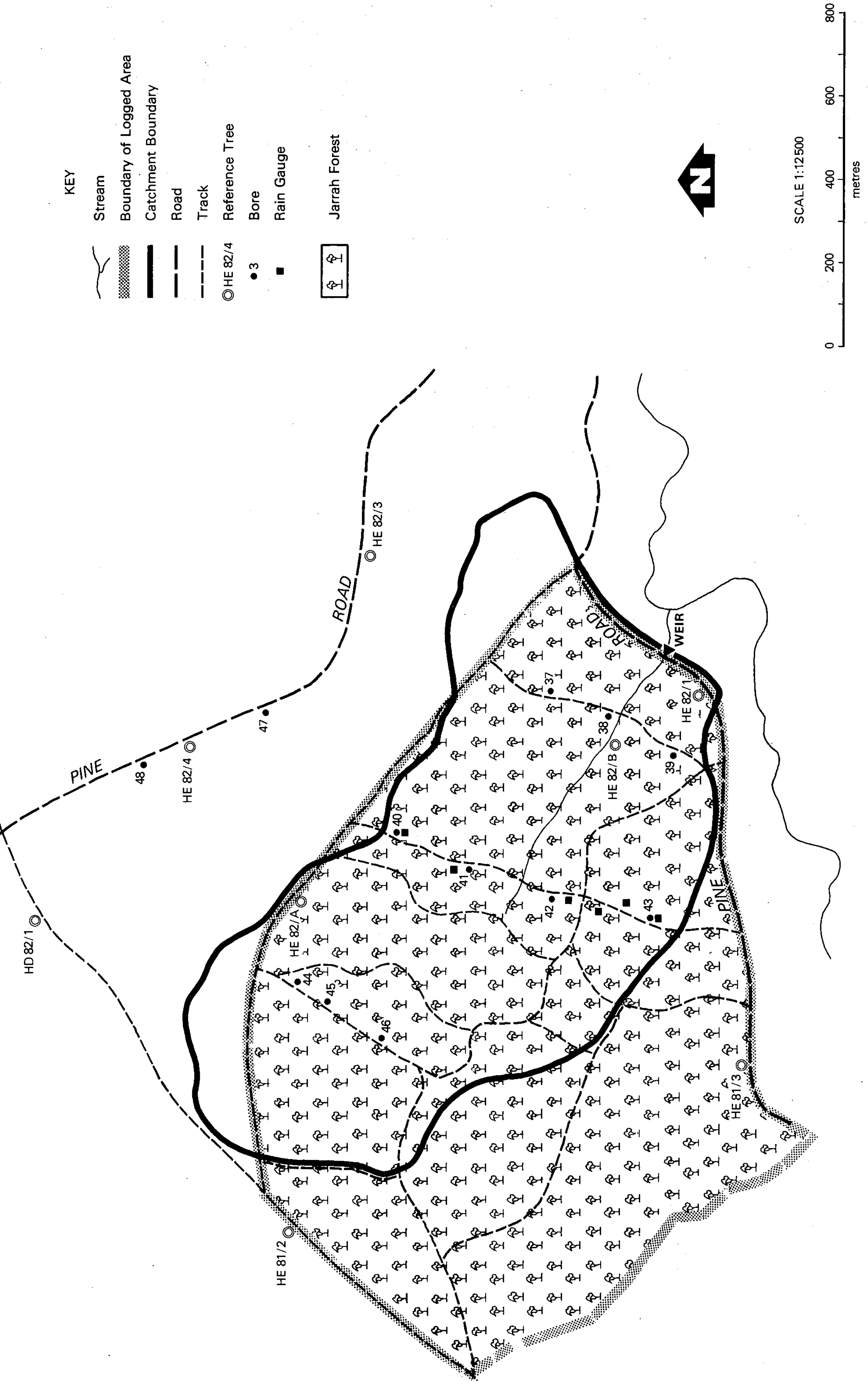
IFFLEY CATCHMENT
AREA LOGGED IN 1976-78



MOORALUP CATCHMENT
SOILS



MOORALUP CATCHMENT
AREA LOGGED IN 1976-77



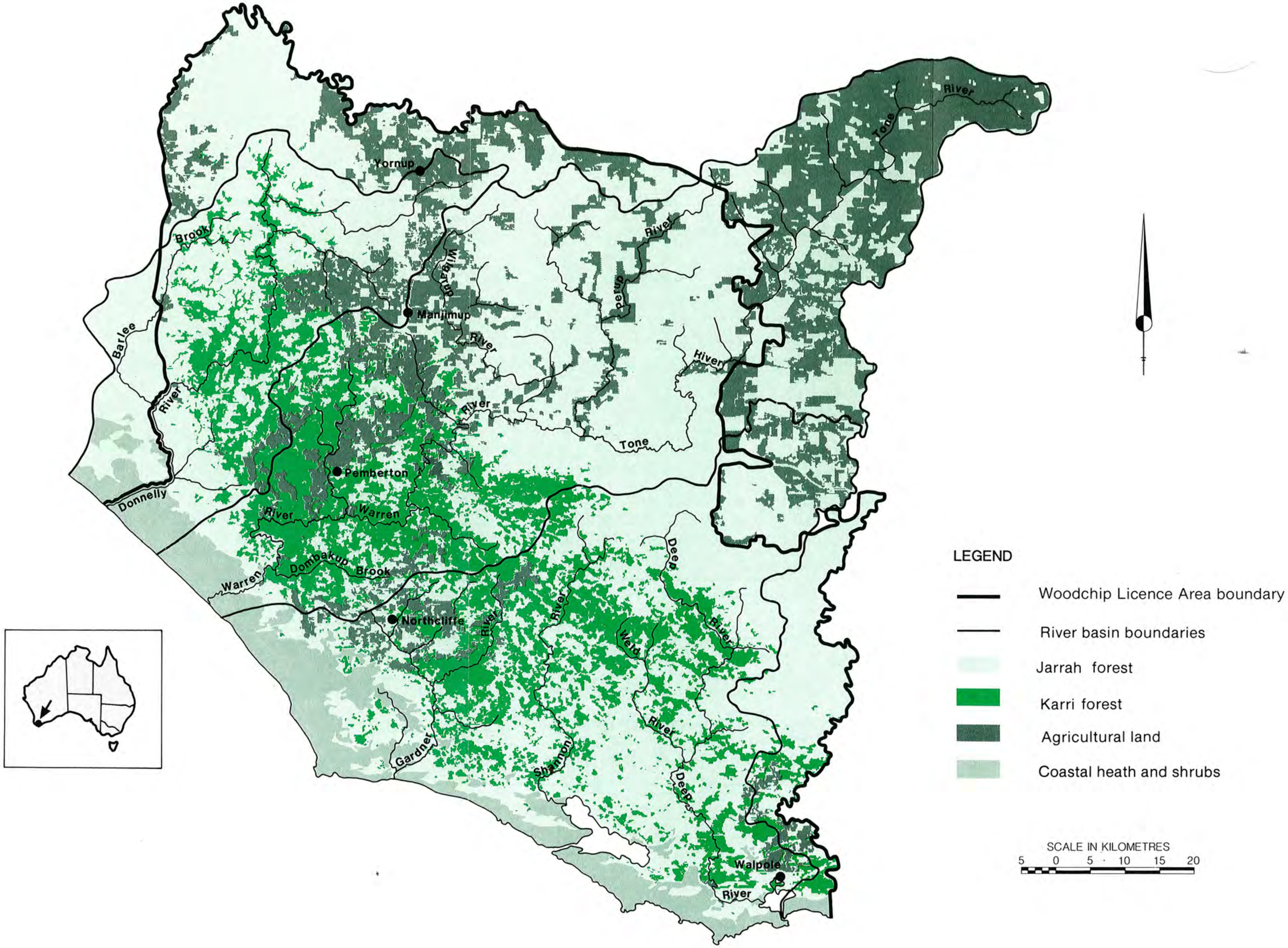


Figure 1

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