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Streamflow and Groundwater Responses to Logging in Wellbucket Catchment, South Western Australia

R. A. Stokes
Water Authority of Western Australia

F. E. Batini
Department of Conservation
and Land Management

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STREAMFLOW AND GROUNDWATER RESPONSES TO LOGGING IN WELLBUCKET CATCHMENT, SOUTH WESTERN AUSTRALIA

R.A. STOKES WATER AUTHORITY OF WESTERN AUSTRALIA

F.E. BATINI DEPARTMENT OF CONSERVATION AND LAND MANAGEMENT

ID. NO. 0030R

ABSTRACT

The effects of logging on the response of saline groundwater and streamflow were observed in a paired-catchment experiment in the Helena catchment in Western Australia. After three years of monitoring one of the catchments, Wellbucket was logged resulting in a 31% reduction in basal area, 42-56% reduction in crown density and an 80% reduction in the volume of trees suitable for firewood.

Small absolute increases in stream water yields of 1.5 - 3.0 millimetre in average rainfall years were estimated to have occurred with an increase in the duration of flow of less than three weeks. Stream water quality did not change significantly as the more saline deeper groundwater did not discharge to the stream.

Increases in bore water levels due to the logging were negligible relative to bores in the catchment not logged. Therefore it was concluded that logging of this intensity would not cause an increase in groundwater levels large enough and for long enough to cause a deterioration in the quality of streamflow because of the relatively large depths to the permanent, saline groundwater in this region.

An assessment of the regional significance of the experimental results was made using soil-vegetation associations and streamflow information for the area of Helena catchment which has average annual rainfalls of less than 900 mm. A regional scale logging similar to the experiment would have little permanent effect on increased streamflow and any increase would be of only marginal benefit to the yield from the Mundaring Reservoir system.

ACKNOWLEDGEMENTS

The rainfall, streamflow and water quality data were collected and processed by Hydrographic staff of the Water Authority of Western Australia. Mr. C. Gilbert and Mr. P. Goodman of the Authority assisted in data analysis and calculation of stream salt loads.

From the Department of Conservation and Land Management Mr. A. Selkirk made many bore water level measurements, Mrs. C. Stone performed chemical analyses and Mr. R. Edmiston carried out the site-vegetation survey. Mr. M. Smith and Mr. J. Meharry were responsible for the field assessments and the logging operation was supervised by the Department staff at Mundaring.

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1. INTRODUCTION

1.1 Background

Mundaring Weir in the Helena catchment, east of Perth (Figure 1), was completed in 1903 for water supply to the semi-arid eastern Goldfields 550 km to the east. In 1903 approximately 8000 ha of native eucalypt forest near the reservoir was ring-barked in an attempt to enhance streamflow (Batini et al, 1978). Although streamflow increased, to the extent that some streams flowed throughout the year, the reservoir salinity rose to 550 milligrams per litre (mg L^{-1}) total soluble salts (TSS). As regrowth forest replaced the original vegetation salinities slowly decreased.

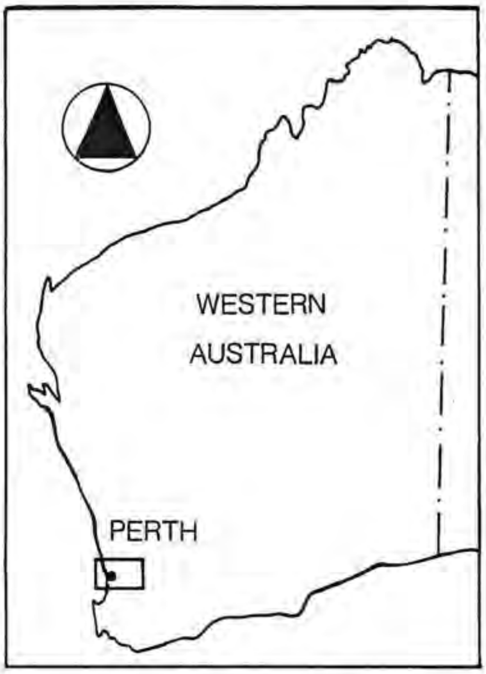
Since the 1960's reservoir salinities have been steadily increasing again to around a mean of 400 mg L^{-1} TSS. This effect has been attributed by Batini et al (1978) to land use changes, particularly agricultural development of forested land in the east of the catchment. In 1979 legislation to control the clearing of alienated land was extended in the Mundaring and three other catchments in the south west (Sadler and Williams, 1981). In addition to agricultural clearing the legislation also imposes restraints on forestry activities such as logging and silviculture.

There is very little information of the effects of logging and silvicultural activities on stream water yield and salinity. Bosch and Hewlett (1982) reviewed world-wide evidence of the relationships between forest thinning and streamflow and concluded that comparatively little was known between the 100% forest and fully cleared states.

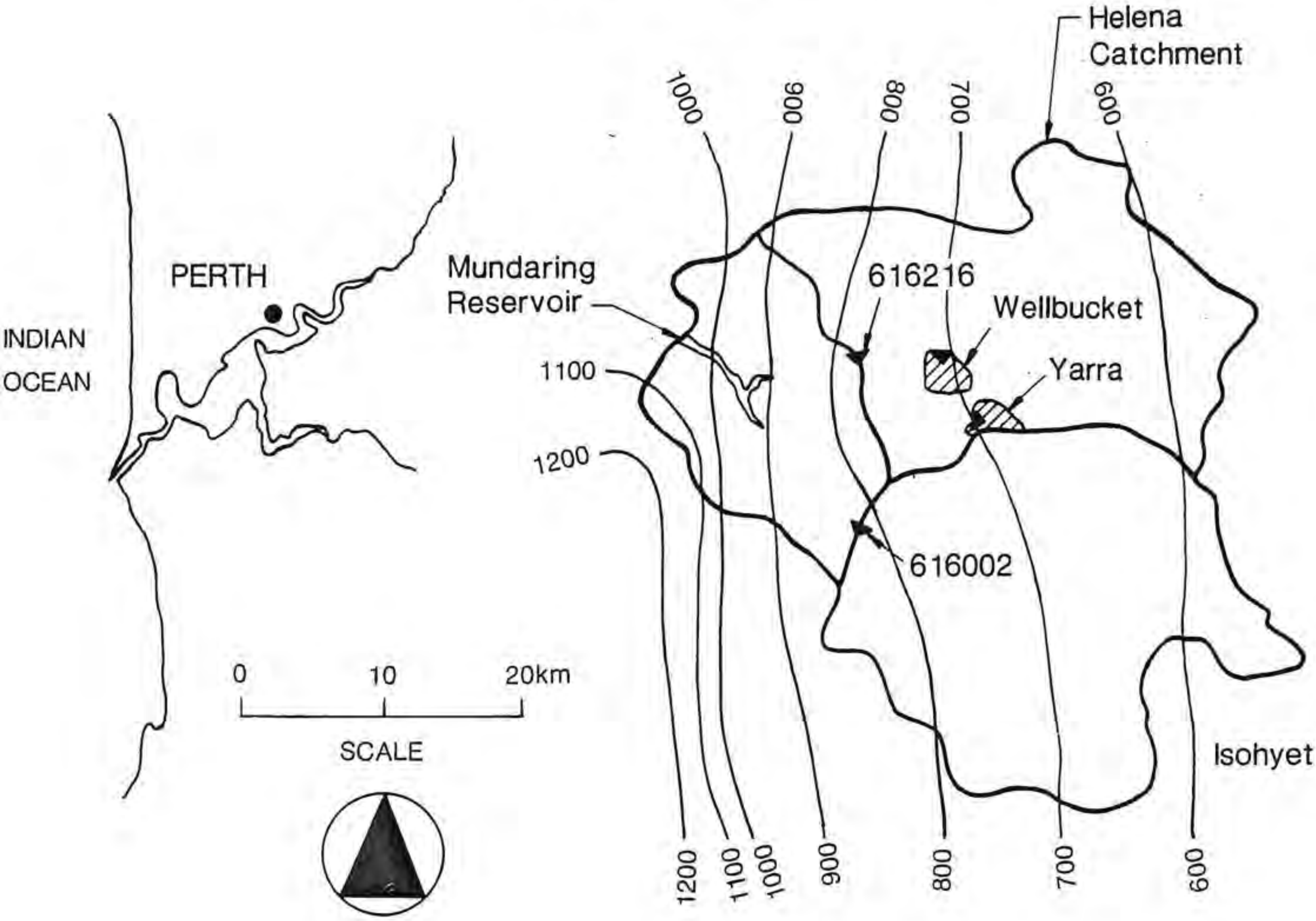
Increased timber and wood product requirements, particularly for charcoal, from the Helena catchment in the 1970's necessitated an investigation of possible hydrological effects of heavy logging.

1.2 Study Aims

In 1974 a paired-catchment study was established in the east of the Helena catchment (Figure 1) to experimentally investigate the effects of logging on the response of saline groundwater and on stream water yield and salinity. The main objective was to determine the magnitude and duration of any increase in streamflow salinity as a result of the logging.



LOCATION MAP



Location Map and Isohyet

FIGURE 1

2. EXPERIMENT

2.1 Location and Climate

The catchments are located about 50km east of Perth (Figure 1). The average annual rainfall is approximately 700mm, 80% of which occurs in the period May to October. Pan evaporation for the area is about 1950mm yr^{-1} with 80% of this occurring between November and April. Salt of oceanic origin is precipitated in rain or as dust and varies from 95 kilogram per hectare (kg ha^{-1} yr^{-1}) TSS in the west of the Helena catchment to 24 kg ha^{-1} yr^{-1} in the east (estimated from Hingston and Gailitis, 1976).

2.2 Topography and Drainage

The topography of Wellbucket (4.65 km^2) and Yarra (6.28 km^2) catchment is subdued, resembling broad saucers, with maximum elevation ranges of 70m and 90m respectively (Figure 2).

Defined stream lines commence in swamp areas only a short distance upstream of each gauging station. In areas adjacent to be swamps surface flow occurs as sheet flow in broad depressions often saturated for short periods.

2.3 Soils and Vegetation

Mapping of the vegetation of the catchment along survey lines of 400m intervals was carried out according to the system developed by Havel (1975 a, b). The surface soils were also mapped using this procedure. Using such field information and aerial photographs, maps of the vegetation and soils were produced (Figure 3) and areas summarized in Table 1.

The forest is predominantly jarrah (E. marginata) with a small component of marri (E. calophylla). Wandoo (E. wandoo) occurs on the valley floors and also on the ridges, especially on lateritic soils which are shallow to clay. On these sites powderbark wandoo (E. accedens) is also found.

The vegetation indicators for soil types are listed in Appendix I. Between 85% and 90% of the catchments consist of sandy soils, lateritic soils and soils shallow to rock. Swamps constitute only 2.7% and 3.6% of Wellbucket and Yarra respectively. Therefore the soils over more than 96% of the catchments infiltrate most of the rainfall.

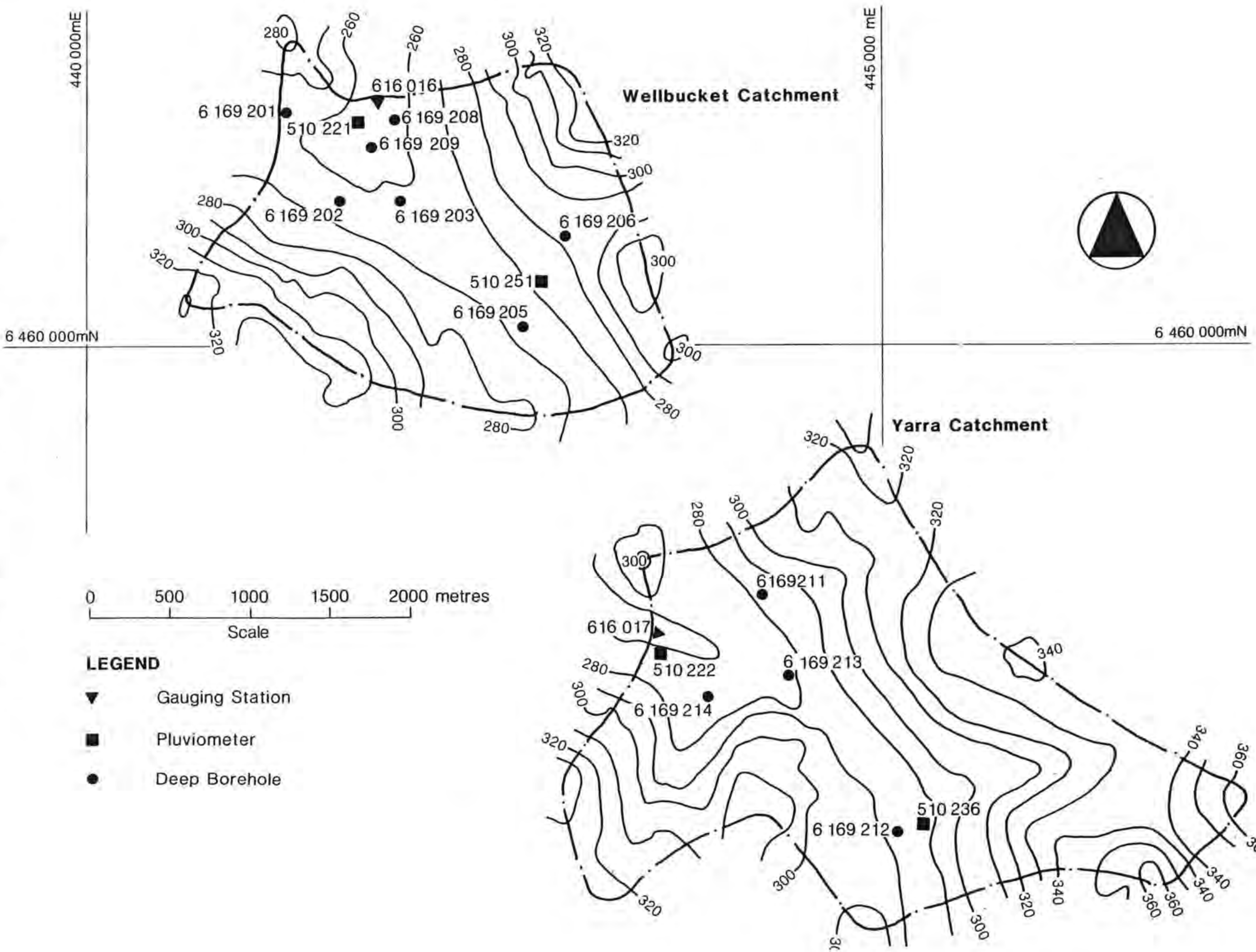
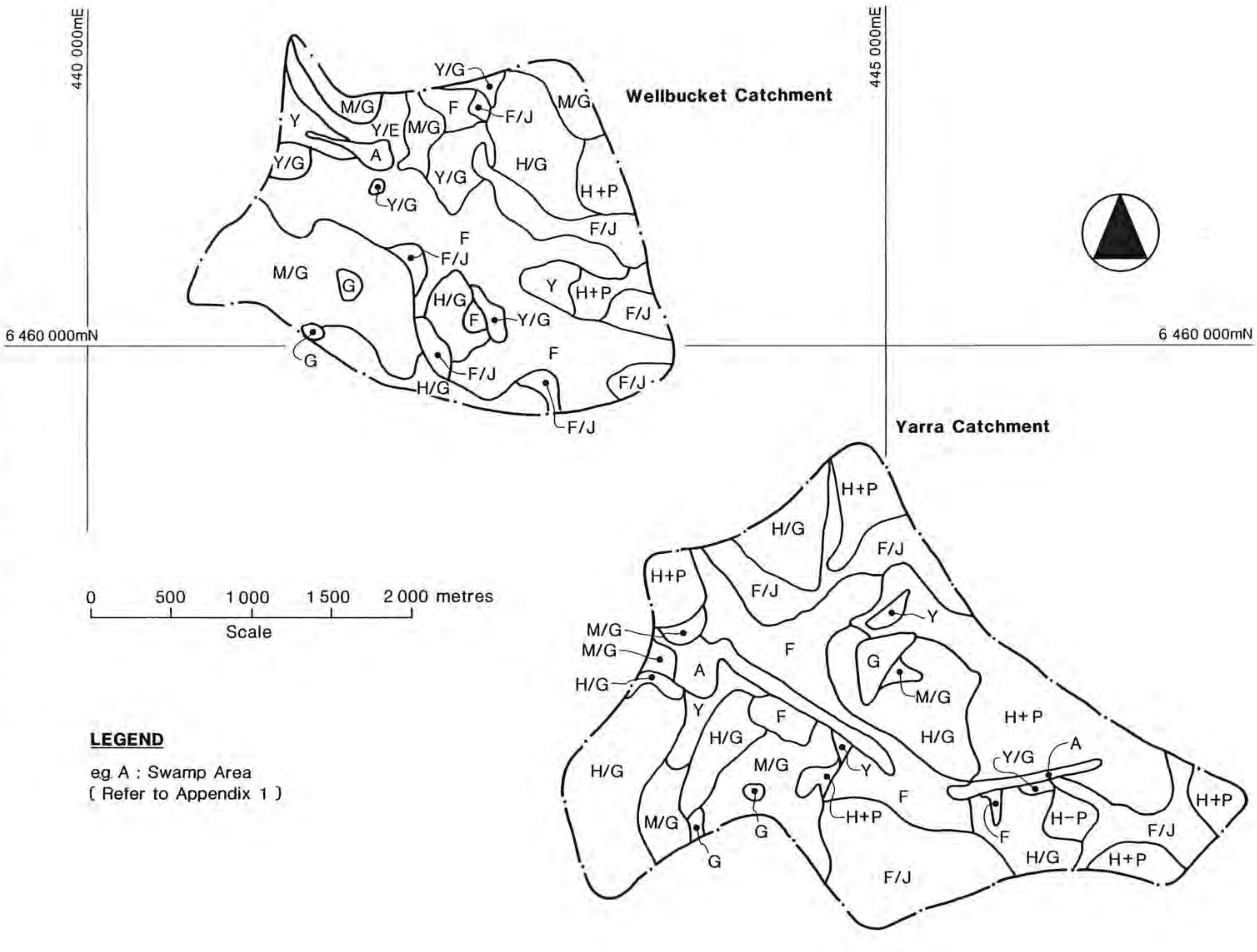


FIGURE 2
Catchment Topography and Instrumentation



LEGEND

eg. A : Swamp Area
(Refer to Appendix 1)

FIGURE 3

Catchment Vegetation - Soil Associations

Table 1. Catchment Vegetation - Soil Associations

VEGETATIVE INDICATORS	WELLBUCKET (%)	YARRA (%)
of swamps (A)	2.7	3.6
of valley floors (Y)	11.2	3.6
of sandy soils (J, F/J)	38.8	31.5
of lateritic soils (H,P,M)	17.9	23.9
of lateritic soils shallow to underlying basement rock (H/G, M/G)	28.7	35.6
of exposed basement rock (G)	0.7	1.8

Notes (i) Developed using Havel (1975a,b) System
(ii) Indicator species listed in Appendix 1, eg. (A)

2.4 Soil Salt Storage and Groundwater

2.4.1 Drilling

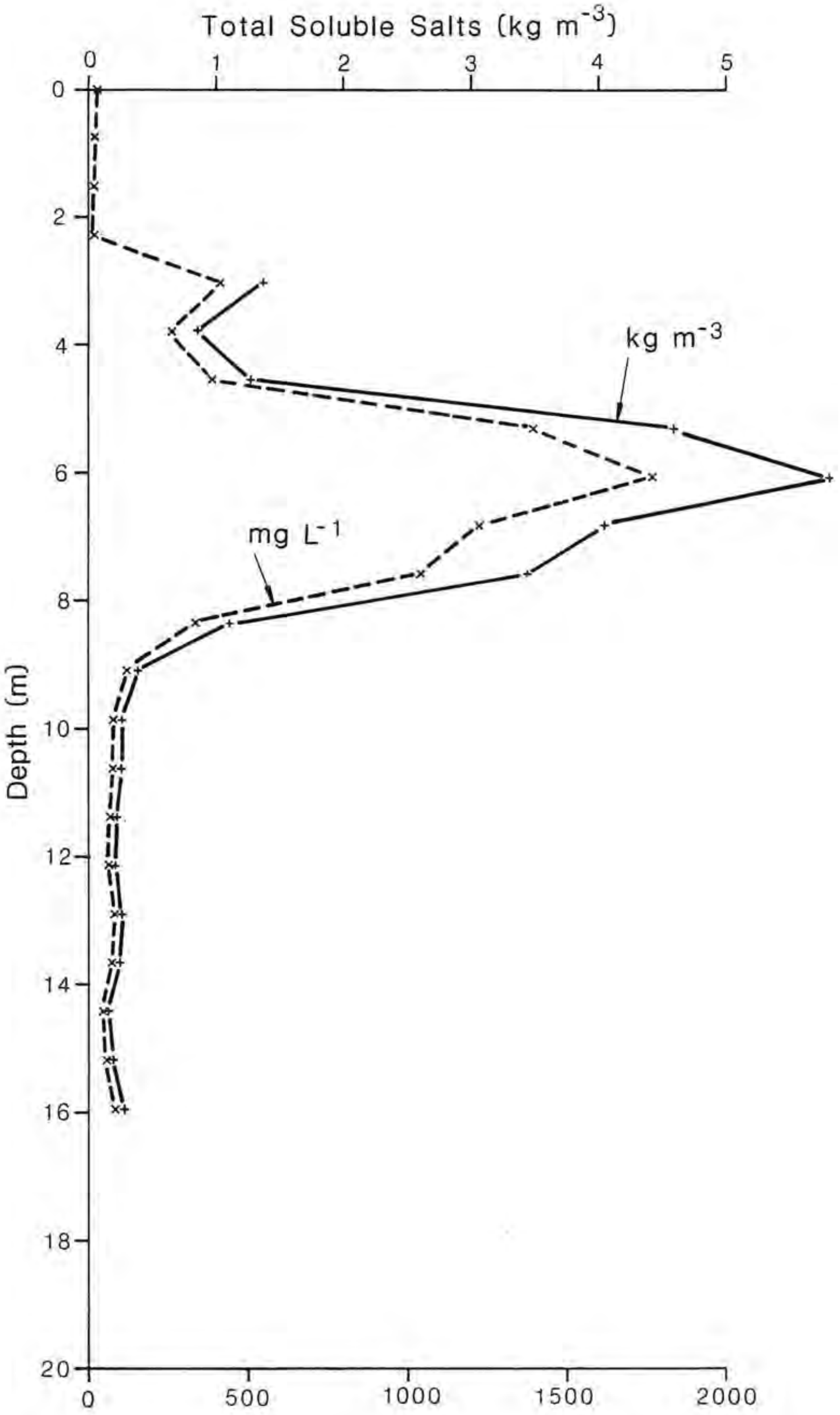
Eighteen deep (more than 8m) and 30 shallow (less than 3m) bore holes were drilled to determine the quantity and distribution of salt in the profile and the level and salinity of the groundwater. Bore locations were selected on the basis of site vegetation type with a greater proportion of holes in the lower topographic areas where the hydrologic effects of logging were likely to be greatest. Details of the drilling, coring and PVC bore installation procedures are given in Batini et al (1976).

2.4.2 Soil Salt Storage

Soil chloride storage averaged 1.35 x 10^5 kg ha^{-1} with a range from 0.08 x 10^5 to 4.9 x 10^5 kg ha^{-1}. Bore locations less than 300m apart had salt storages which differed by a factor of 40 (Batini et al, 1976). The average soil chloride storage is slightly lower than would be expected for the rainfall of 700mm (Dimmock et al, 1974). The quantity of salt stored per unit of landscape appears to be related to vegetation type. Types J, F/J and M/G (sandy/lateritic soils) were generally low in stored salts. The valley floor sites (Y) had a prominent saline band (or bulge) between 3m and 11m. In the finer textured soils the store of salts was concentrated in the region above the bore water level and below the sandy, gravelly surface soil horizons (Figure 4).

2.4.3 Water Levels

Groundwater levels in the deeper bores were below the prominent soil salt storage zone in the valley sites. The average depth to groundwater in the deeper bore holes was about 10m with a range of 5m to 20m (Batini et al, 1977). Often no groundwaters were found in lateritic upland areas whereas water levels were within 8m of ground level in bores close to the stream gauging stations. It is unlikely therefore that the deeper groundwaters contribute to streamflow. The results of the drilling indicated that groundwaters were not areally extensive in either catchment.



Soil Salt Storage at Yarra Bore 6 169 211

FIGURE 4

2.5 Hydrology

2.5.1 A Conceptual Hydrologic System

A pictorial representation of the forest hydrological system as it may apply in the eastern Helena catchments is shown in Figure 5. The profile consists of surficial sands, gravels and loams 0-5m thick overlying a mottled to pallid clay material transitional through a weathering zone to parent bedrock at depths of typically 20 to 30m. Saturated hydraulic conductivities in the surface material may be of order 2m day^{-1} (Sharma et al, 1980) and several orders-of-magnitude smaller in the underlying clays (Peck et al., 1980).

During winter saturation may occur in the surface soils above a lateritic caprock, silaceous hardpan or clay forming a perched groundwater. Up to 10-15m of the underlying profile remains unsaturated until a (permanent) zone of saturation is reached in the deeper pallid clay and weathering zone above the bedrock. Recharge from the surface soils to the deeper groundwater occurs seasonally via the clay matrix of the unsaturated zone and via preferred pathways in the matrix such as root channels (Johnston et al, 1983; Dell et al, 1983).

The deeply weathered profile provides a considerable soil water store and therefore source of water for transpiration by the deep-rooted eucalypt vegetation during the relatively dry summer (Dell et al, 1983). Sharma (1984) noted a seasonal soil water storage capacity of 450mm in the top 6m of a freely-drained (water table 10m) forested site elsewhere in the south west of Australia.

2.5.2 Observations of Streamflow Generation

There was no visual evidence of surface runoff, even during heavy rainfall, from the lateritic and sandy soils and none was observed from the flats adjoining the swamps. Surface runoff was observed, from the swamps, particularly following saturation, in the form of shallow, sheet flow. These areas were of limited extent and were confined to the streamlines.

During winter the swamps slowly became saturated, as evidenced by water levels in several shallow bores. Perched water tables developed in the swamps, in the flats which adjoin these and on some sandy soils which were shallow to a hardpan or clay. Drilling of shallow bores in the lateritic soils was not possible by hard-auger and data for those sites are not available. However these are well-drained soils and

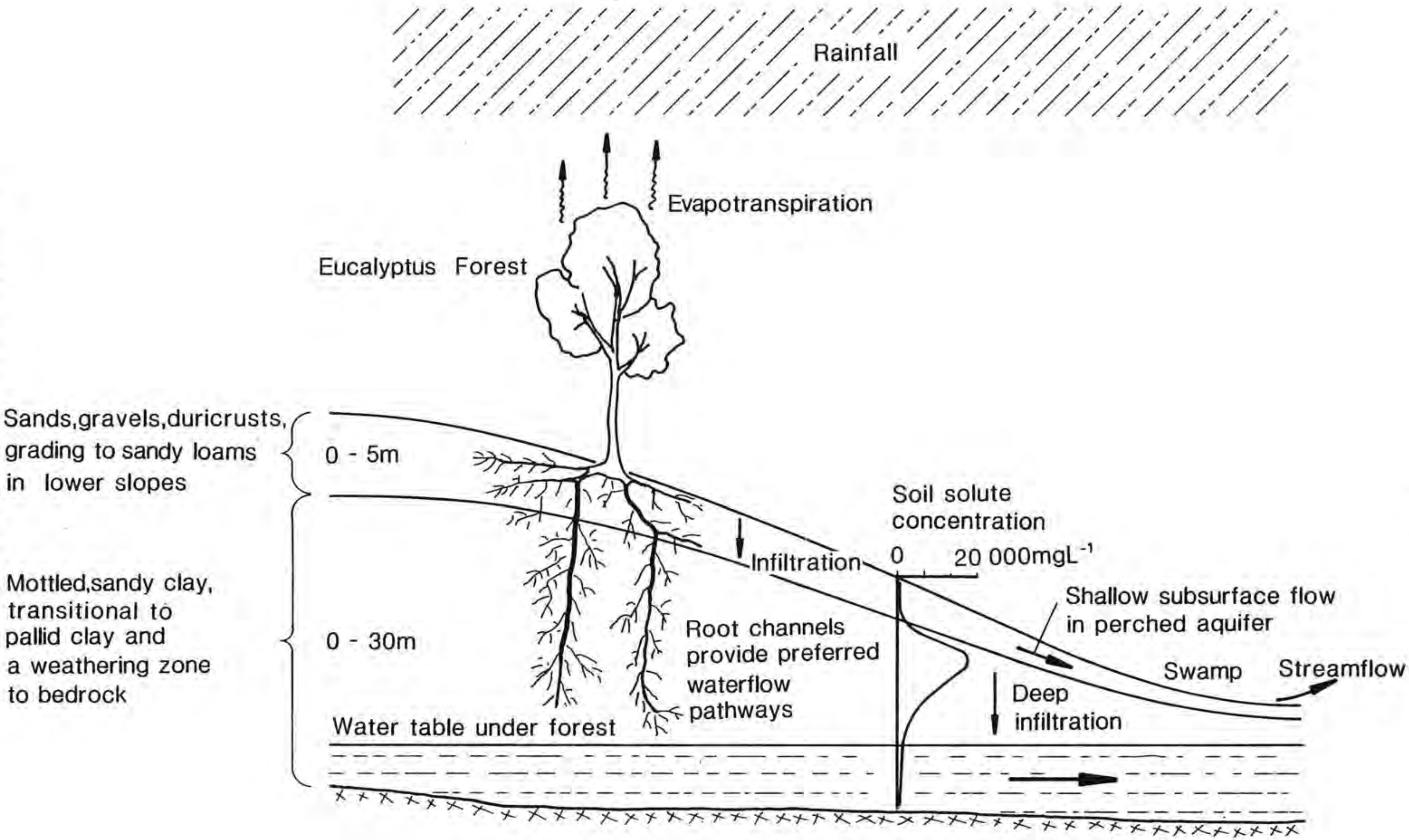


FIGURE 5

Forest Hydrological System
(Adopted from Sharma and Williamson , 1984)

it is unlikely that a perched water table develops in these situations. Shallow bores in the deeper, sandy soils were generally dry.

The water level response to rainfall in the shallow bores in the swamps were generally more dampened than that of bores on adjoining flats and sandy slopes. This was because once saturated the swamp bore water levels remained close to ground level whilst upslope bores drain, laterally and vertically, more dynamically.

The water quality of these shallow, seasonal groundwaters (Batini et al, 1977) were very similar to that of streamflow.

2.6 Instrumentation

2.6.1 Streamflow

Streamflow was recorded by a float driven 'A35' Leupold and Stevens chart recorder with a small concrete stilling basin and combination sharp-crested weir plates consisting of 60^{o} V notch and 1:10 walls as control. Less than 2% of record was lost at either station and this occurred during periods of no or little streamflow.

2.6.2 Rainfall

Four tipping-bucket pluviometers (Figure 2) recording onto Leupold and Stevens A35 chart recorders provided rainfall data. Catchment daily rainfall totals were calculated using the Thiessen Polygon method.

2.6.3 Water Quality

Stream water quality was obtained by weekly hand samples in 1974 and 1975 and by automatic pumping samplers (PWD mk3) from 1976. Samples were analysed for electrical conductivity, chloride and occasionally for all major ions.

2.7 Treatment

Both catchments had been cut-over for sawlogs; Yarra Road in the period 1958-60 and Wellbucket before this time. The catchments were "advance burnt" in the spring of 1974, and have not been burnt since.

Data for the forest in the Wellbucket catchment were obtained from assessment along North-South strip lines 10m wide and spaced 200 m apart. Lines were blazed and marked at each 100 m station to assist relocation. Twenty hectares (4.3 percent) of the catchment were assessed.

Estimates of Crown cover were obtained with a densiometer. Tree crowns are reflected onto the mirror face of this hemi-spherical instrument. The face is divided into squares and the percentage crown cover is estimated by summing the crown cover on each square. At each 100 m station four estimates of crown cover were obtained, at subsamples located 25 m from the station, along the cardinal point of the compass.

In the Wellbucket catchment trees with a commercial sawlog were marked for retention and then all trees suitable for charcoal production were felled in the summer of 1976/77. After felling was completed the catchment vegetation was reassessed, including estimates of crown density. Vertical aerial photographs (1:10000, 1981) of the catchments were available for interpretation. Crown cover at 20 randomly selected sites on each catchment were estimated, by comparison with density scales.

3. RESULTS

3.1 Vegetation

Representative vegetation data for Wellbucket catchment are shown in Figure 6. These show substantial reductions in crown density of 42-56% (Figure 6b) and volume of standing firewood of 80% (Figure 6c). Basal area(not shown) decreased by 31% from 16.2 to 11.1 m^2 ha^{-1}.

Stem numbers for trees greater than 60cm decreased by 55% (Figures 6a) whereas total stem numbers decreased by only 14%. The total stem number was least altered by cutting because of the uneven distribution by size classes and the commercial need to remove the larger trees. This may account for the incomplete removal of firewood logs in the 30 to 60cm class. In the over 60cm class a number of the Wandoo had extensive heart - rot and were not removed.

Estimates of the volume of marri remained little changed as this species was not suitable for charcoal production.

Measurements of crown density showed a significant reduction and data indicates that the felled trees had larger than average crowns. Although crown density was not measured subsequently, by 1982 advance growth was 2-3 m high, coppice had reached 3-7 m in height and seedling regeneration had occurred.

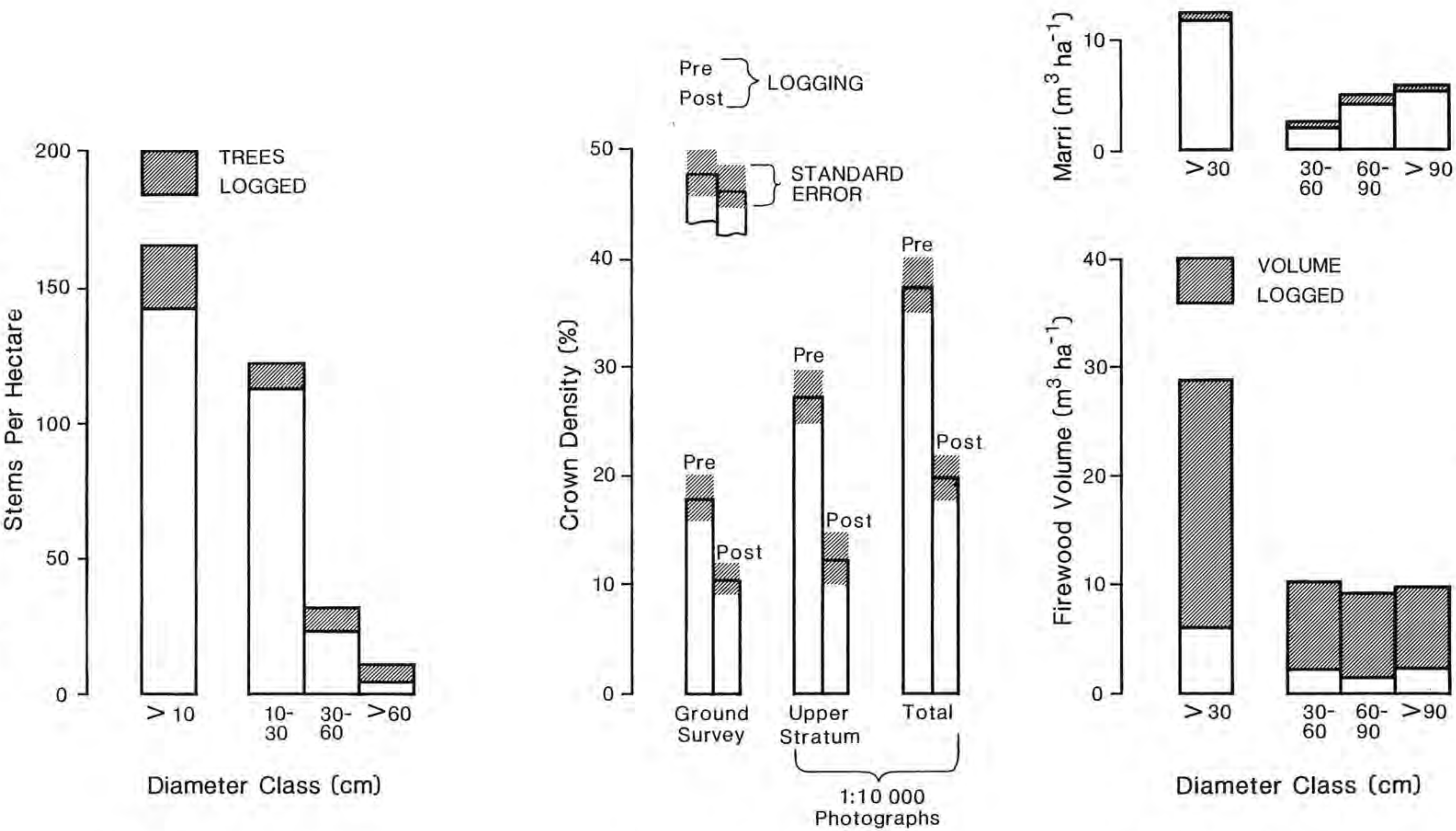
3.2 Groundwater

3.2.1 Water Levels

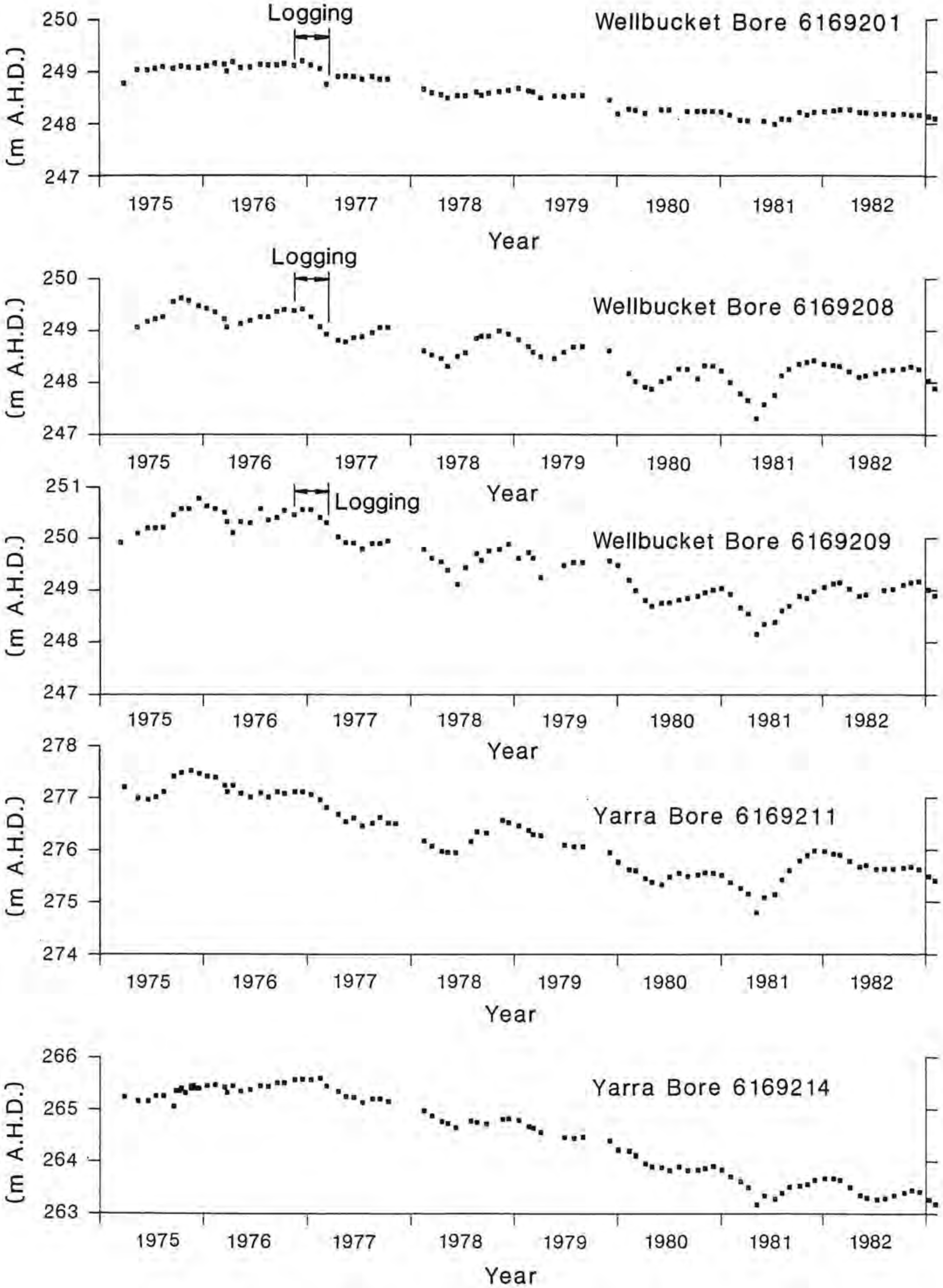
Seven bores in Wellbucket and four in Yarra were selected to monitor the effect of logging and to function as control bores respectively. Five of these bores (Figure 2) were chosen to be monitored after 1979 (bores 201, 208, 209 and 211, 214) where accumulation of groundwater was anticipated.

The response of bore water levels to rainfall over both pre-treatment and post-treatment periods were gradual. Seasonal maxima were observed between October and December and minima between March and May (Figure 7). Minimum water levels have shown a gradual decline from 1975 to 1980 which was a period of generally below average winter rainfall. Some recovery of water levels occurred in 1981 as a result of above average rainfall.

FIGURE 6 Wellbucket Vegetation Inventory



a. Stem Numbers **b. Crown Density** **c. Wood Volume**



Groundwater Levels

FIGURE 7

The change in minimum water levels over three year periods, 1977-1975 for pre-treatment and 1979-1977 for post-treatment are listed in Table 2. On the control catchment, all bores show decreases which are greater than bores on the treated catchment. Of the seven bores in Wellbucket, six had decreases in water level following thinning which were greater than or equal to the pre-logging decreases.

Table 2. Seasonal Minimum Water Levels

Bore	Change in Minimum Levels (m) 1977-1975	 1979-1977
Wellbucket		
201	-0.1	-0.45
202	-0.05	-0.3
203	-0.3	-0.3
205	-0.3	-0.15
206	-0.2	-0.4
208	-0.3	-0.3
209	-0.35	-0.5
x(s)	-0.23 (0.11)	-0.34 (0.12)
Yarra		
211	-0.55	-0.6
212	-1.8	-0.9
213	-0.8	-0.5
214	-0.4	-0.7
x(s)	-0.89 (0.63)	-0.68 (0.17)

X(s) : mean and standard deviation

Water levels of bores in Wellbucket (numbers 201, 208 and 209) are shown plotted against bore water levels in Yarra (numbers 211 and 214) in Figure 8. The data for the pre-logging period generally plots in the top of each graph with lower levels occurring in the post-logging period due to a run of below average rainfalls. This makes detection of changes difficult because the range of water level variations are different between pre and post logging.

Minimum water levels were selected for analysis because these indicate net groundwater accretion and therefore whether any real rather than seasonal change has occurred. (A reading was obtained in June 1985, two years after the end of the experiment to check for any further changes; data shown in Figure 8)

The response of the Wellbucket bore water levels relative to Yarra 211 (Figure 8 a, b, c) do not indicate any marked change. However plotted against Yarra 214 the water levels in Wellbucket appear to have increased by up to 1 m (Figure 8 d, e, f) since 1980 or 1981. This apparent difference in response of Wellbucket bores relative to the two bores in Yarra, three to four years after logging, raises the question of the reliability of the Yarra bores as controls.

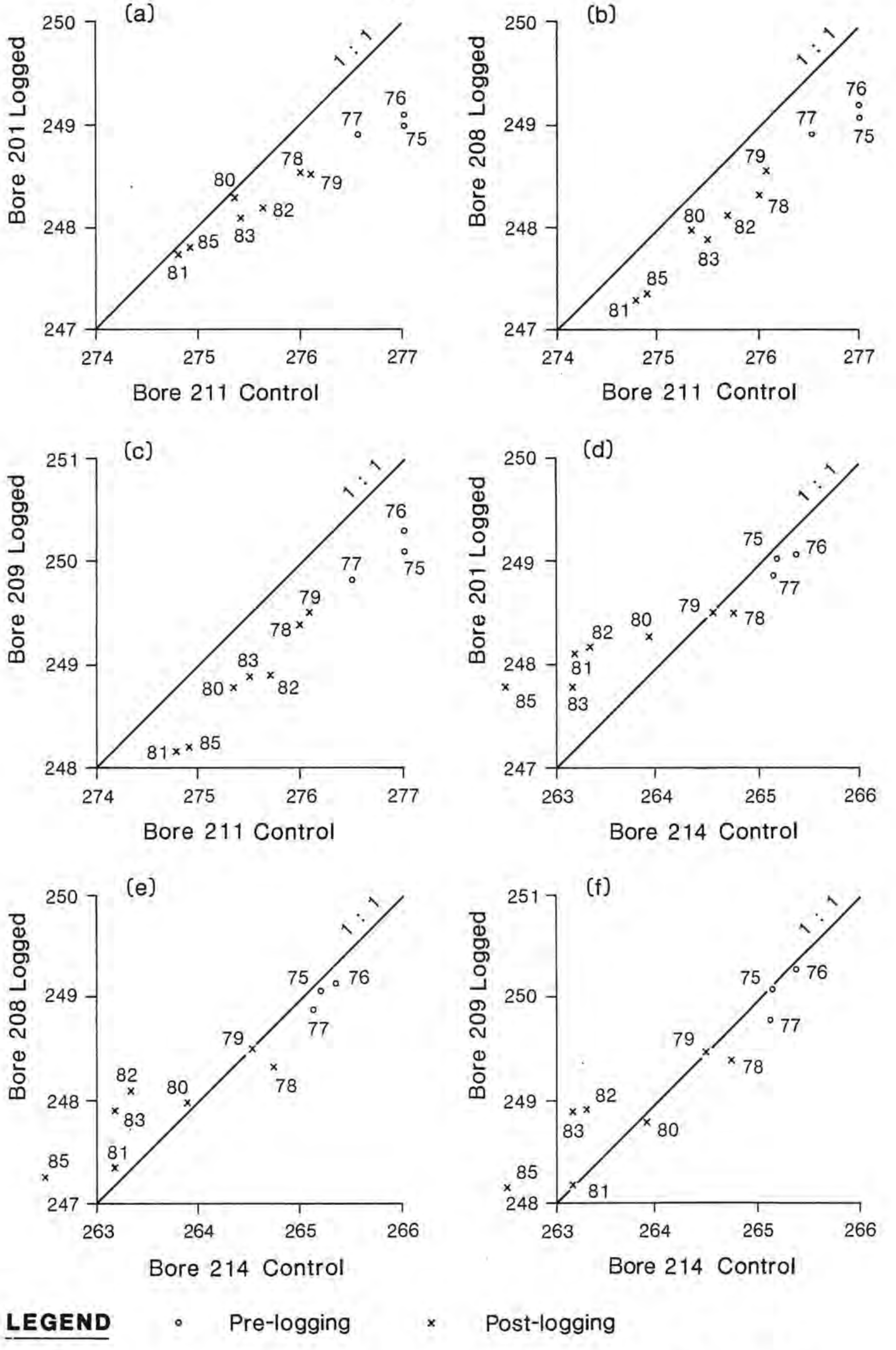
As these bores are in the control catchment it was expected that their relative response would be similar, or at least consistent. This is the case for the 1975-1981 period (Figure 9) where the linear relationships is :-

$$Y = 7.91 + 0.93.X \text{ with } r^2 = 0.96,$$

where Y and X are water levels for bores 214 and 211 respectively. The slope of the line is 0.93 over the 1975-1981 period which is close enough to 1.0 to indicate that over this time the two control bores responded similarly.

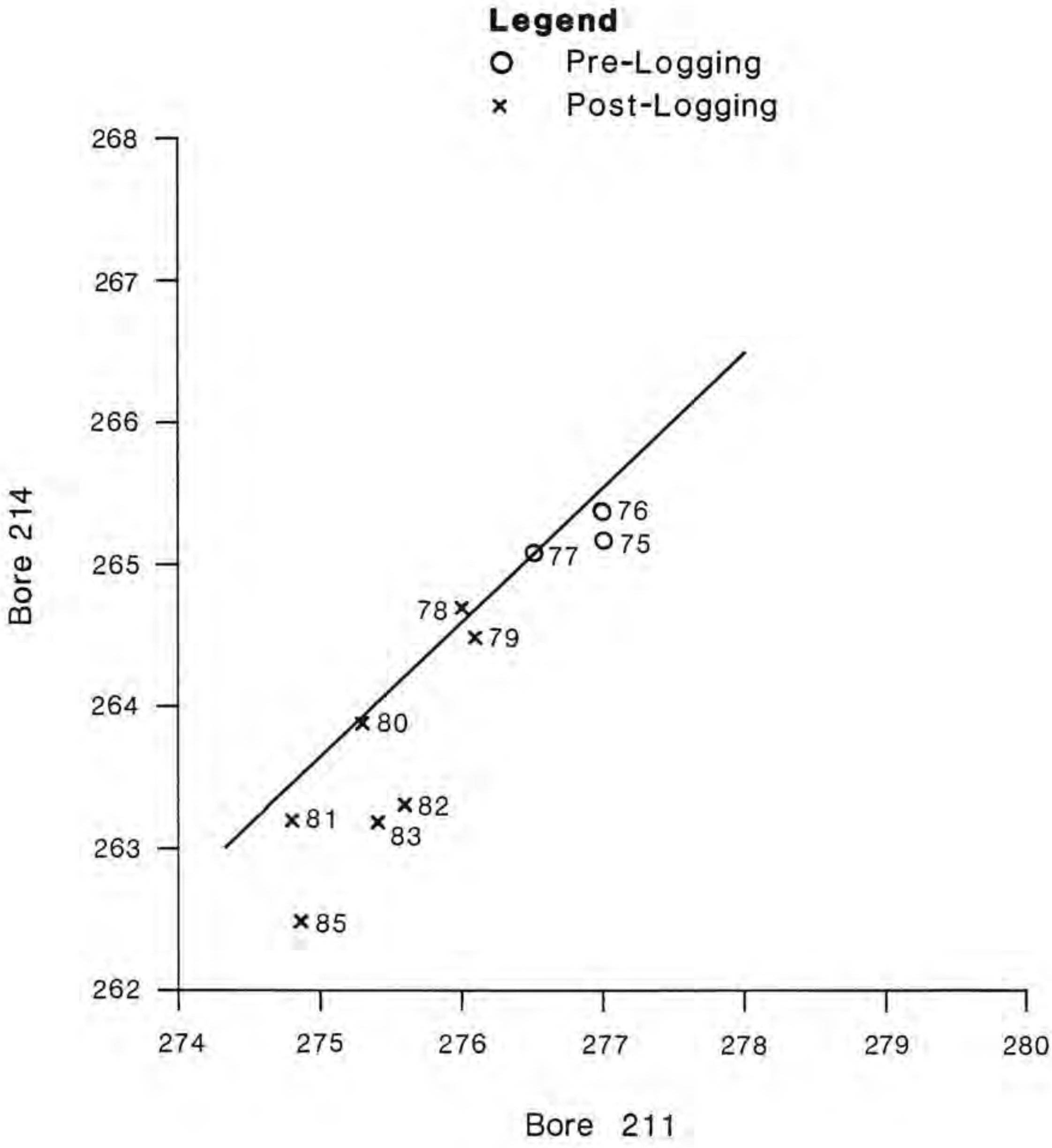
However from 1982 (possibly even from 1981) the relationships fails as either 211 has increased or 214 has decreased relatively. The June 1985 check reading indicated that bore 214 was dry (that is the water level was below 262.5m AHD). Of the two possibilities therefore it appears (see also Figure 7) that the groundwater level as monitored by bore 214 decreased since 1981 - 1982.

The implication of this is that the apparent increase of up to 1m in levels in the Wellbucket bores (Figure 8 d, e, f) is not an effect due to logging but is due to a decrease in water level in the control bore of



Logged versus Control Bore Water Levels (m A.H.D.)

FIGURE 8



Control versus Control Bore Water Levels (A.H.D. m)

FIGURE 9

more than 0.8m (Figure 9). Therefore there was no significant (more than 1m), sustained increase in bore water levels in Wellbucket in response to logging.

3.2.2 Groundwater Flow from Catchments

A more saline groundwater, deep in the profile above bedrock was observed by Batini et al (1977). Groundwater levels were more than 5m below ground level near the stream gauging stations with a saturated depth of about 15m. Although these groundwaters are not known to contribute to streamflow it was considered instructive to calculate possible groundwater outflow beneath the surface divide. This is done by assuming steady state, average conditions using Darcy's law :-

$$q = k.i.d \qquad (1)$$

where q is discharge ($m^3 day^{-1}$ per unit width), k is hydraulic conductivity ($m\ day^{-1}$), i is hydraulic gradient ($m\ m^{-1}$) and d is depth of flow (m).

From bore hole slug tests Peck et al. (1980) determined a mean hydraulic conductivity of 6.7 x 10^{-2} m day $^{-1}$ for these catchments. A gradient of 0.01 m m^{-1} was estimated from water levels of bores near the catchment boundary.

With the assumptions and parameters, groundwater underflow at Wellbucket could be 10^{-2} m^2 day^{-1} per unit width of flow (which is unknown). If a nominal flow width of 100m is taken then underflow could be of order 400 m^3 yr^{-1} which represents a catchment averaged depth of less than 0.1 mm year.

3.3 Catchment Water and Chloride Balances

3.3.1 Method

Catchment inputs (rainfall) and outputs (streamflow) were calculated for water years commencing in April. Water was expressed as a catchment area-depth equivalent (mm) and chloride as mass per hectare (kg ha^{-1}). The input of chloride was estimated from rainfall by using an average rain chloride ion concentration of 5.5 mg L^{-1} interpolated from the work of Hingston and Gailitis (1976).

Catchment to catchment comparisons, pre and post logging, were made using water and chloride output to input ratios expressed as a percentage.

3.3.2 Water Balance

Wellbucket and Yarra water and chloride inputs, outputs and balances are listed in Table 3.

Yearly rainfall varied by almost 40% above and below the longer term average of 700 mm (Hayes, personal communication) with an average of 690 mm over the eight years. Although the highest rainfall was recorded in 1981/82 the winter rains of 1974 were more effective in producing streamflow which was approximately twice that produced in 1981.

The maximum streamflow yield for Yarra in 1974 was 2.5% of rainfall and the minimum of 0.04 mm or 0.007% of rainfall occurred for Wellbucket in 1976 (Table 3). Clearly the yearly variability of streamflow is much greater than rainfall. The runoff from Yarra has been two to twenty times that from Wellbucket. Streamflow is not a major component of the water balance. The mean yearly runoff for Wellbucket and Yarra over the eight years were 2.7 mm and 6.8 mm respectively.

An estimate of evapotranspiration, the major component of the water balance, can be obtained from the water balance equation:-

$$ET = R - S - WW - WG \qquad (2)$$

where ET is evapotranspiration, R is rainfall, S is streamflow, WW is change in soil water storage and WG is change in groundwater storage.

Sharma et al, (1982) indicated that over a year the WW term is approximately zero. An estimate of WG can be obtained by considering the average change in bore water levels, multiplied by a storage coefficient of 0.04 (Bestow, 1976). Per year WG is about 4 mm which is insignificant in terms of annual rainfall. Therefore ignoring WG, the water balance equation reduces to:

$$ET = R - S \qquad (3)$$

and the yearly results are listed in Table 4.

The average ET for both catchments was 683 mm yr^{-1} with a standard deviation of 149 mm. This represents approximately 35% of the average annual pan evaporation. Even in 1981/82 for Yarra ET was only 50% of pan evaporation. The catchment water balance is dominated by evapotranspiration with more than 97.5% of rainfall being intercepted and evaporated and/or transpired by vegetation.

TABLE 3

CATCHMENT WATER AND CHLORIDE BALANCES

	Rainfall Input		Stream Outflow			Outflow/Input	
Water Year	Water (mm)	Chloride (kg ha^{-1})	Water (mm)	Chloride (kg ha^{-1})	Chloride (mgL^{-1})	Water (%)	Chloride (%)
WELLBUCKET (4.65 km^2)							
1974/75	852	46.9	11.47	2.5	22	1.346	5.3
1975/76	778	42.8	1.43	0.3	21	0.184	0.7
1976/77	547	30.1	0.04	0.01	22	0.007	0.03
1977/78	568	31.2	0.08	0.02	21	0.014	0.06
1978/79	722	39.7	2.47	0.6	26	0.342	1.5
1979/80	506	27.8	0.13	0.02	18	0.026	0.07
1980/81	623	34.2	0.14	0.02	17	0.022	0.06
1981/82	912	50.2	5.47	2.59	32	0.600	5.16
YARRA (6.28 km^2)							
1974/75	851	46.7	21.61	7.8	36	2.539	16.7
1975/76	778	42.8	9.30	3.5	38	1.195	8.2
1976/77	547	29.7	0.83	0.21	26	0.154	0.71
1977/78	555	30.6	0.83	0.28	34	0.150	0.92
1978/79	705	38.8	8.81	3.5	40	1.250	9.0
1979/80	490	26.9	0.66	0.20	31	0.135	0.74
1980/81	618	34.0	1.18	0.27	23	0.191	0.79
1981/82	968	53.2	11.13	10.07	37	1.150	18.93

Note: Water Year commencing in April

TABLE 4

CATCHMENTS EVAPOTRANSPIRATION

Water Year	Evapotranspiration (mm) Wellbucket	Yarra
1974	841	829
1975	777	769
1976	547	539
1977	568	554
1978	720	696
1979	506	489
1980	623	617
1981	907	957
Mean	686	681

3.3.3 Chloride Balance

3.3.3.1 Calculation of Stream Chloride Yield

Stream chloride yields were calculated using the continuous flow record and water quality samples. This procedure is reasonably accurate when the frequency of sampling is at least daily or when streamflow and hence water quality are not changing rapidly. This did not apply in 1974 and 1975 where, as can be seen in Table 5, relatively few samples were collected.

As a result of insufficient samples, it was necessary to develop a relationship between the four samples and the corresponding stream discharge. The form of the relationship developed was based on that of Hall (1970):-

$$C = (S - C_o)/(1 + BQ^{1/n}) + C_o \qquad (4)$$

where C is the stream salinity (mg L^{-1}), Q is stream discharge (m^3), S and C_o are asymptotic salinity at very low and very high discharge respectively (mg L^{-1}). For forested areas in the eastern Mundaring catchment S and C_o represent the salinity of shallow groundwater seepage and surface runoff water respectively. The parameter B affects the proportion of flow from groundwater relative to total flow and n is a function of the assumed storage-discharge relationship for the catchment.

The values of S and B were varied seasonally, being calculated at each sampling time and interpolated between sampling times on the basis of accumulated flow volume. Thus a continually changing flow-salinity relationship was obtained and integration used to calculate daily and yearly chloride loads in streamflow.

3.3.3.2 Chloride Balance

Proportionally more chloride than water is discharged from the catchments in streamflow (Table 3). Yarra catchment in 1981 output 19% of the estimated chloride input compared with less than 1.2% of rainfall output as streamflow. Nevertheless both catchments are acummulating chloride in the soil profile because the water balance is dominated by evapotranspiration.

TABLE 5

FLOW DURATION AND NUMBER OF STREAM WATER SAMPLES

Water Year	Wellbucket Days of flow	Wellbucket Samples	Yarra Days of flow	Yarra Samples
1974/75	171	26	165	24
1975/76	116	17	122	54
1976/77	11	14	35	24
1977/78	16	20	23	26
1978/79	96	73	105	126
1979/80	8	3	30	16
1980/81	67	29	67	51
1981/82	157	250	144	261

3.4 Streamflow Response

3.4.1 Water Balance

Three years of data (1974-1976 winters) were available with which to establish a catchment to catchment calibration for the purpose of determining streamflow changes. Clearly this is too few data to determine meaningful statistical confidence on the correlation. For this reason two simple models of the relationship between Wellbucket and Yarra water year output to input (%) were developed:-

$$\text{Model 1 : } W = -0.019 + 0.170Y \quad Y \quad 1.195 \qquad (5a)$$
$$W = -0.850 + 0.865Y \quad Y \quad 1.195 \qquad (5b)$$

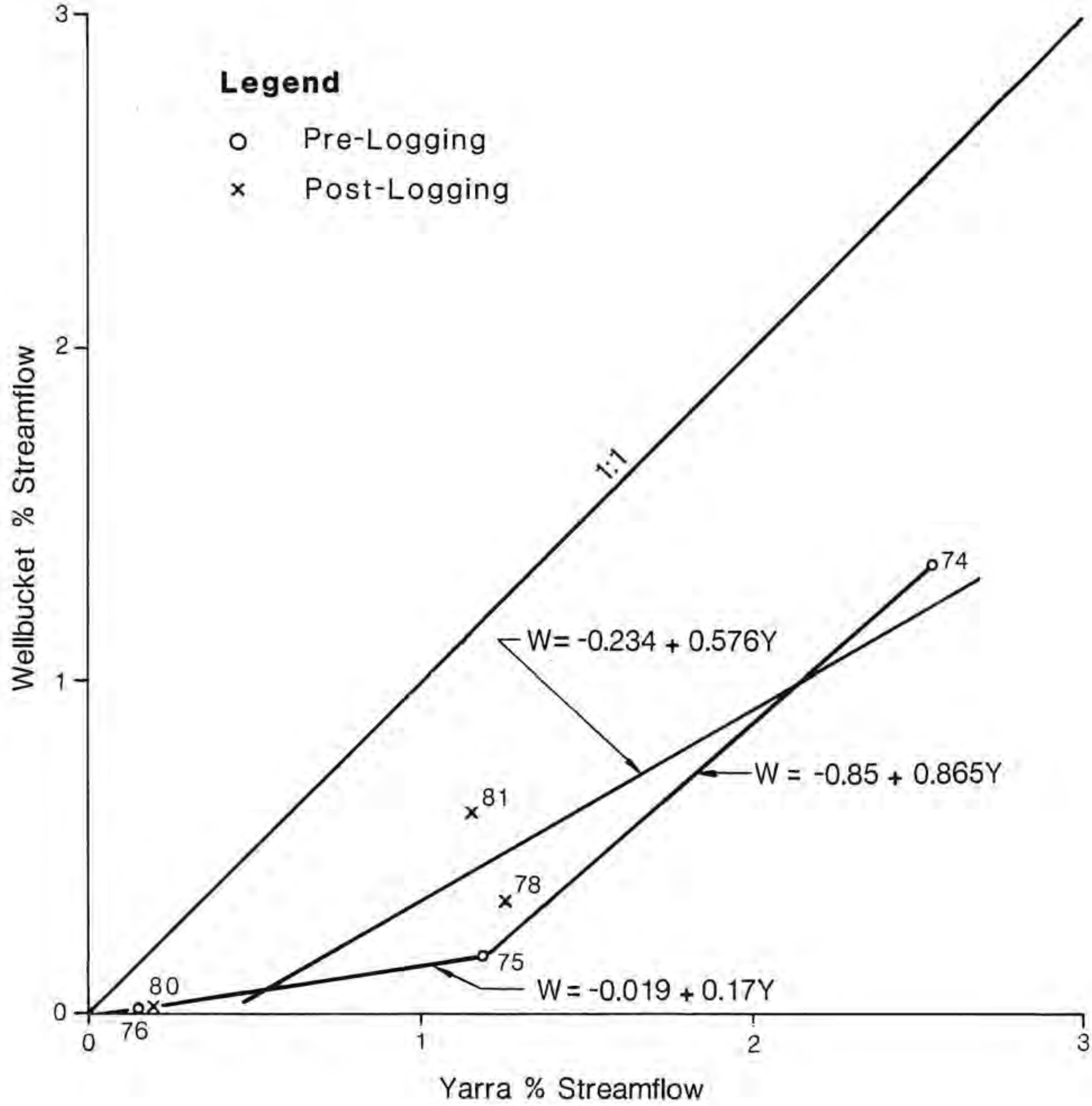
$$\text{Model 2 : } W = -0.234 + 0.576Y \qquad (6)$$

Whereas model 2 is fitted by linear regression to the three points model 1 assumes a piece-wise linear 'perfect fit' between 1976-1975 and 1975-1974 (Figure 10).

The Wellbucket observed (%), predicted (%), difference (observed-predicted %) and difference (mm) are listed in Table 6. There are several important differences in the results produced by the two models, the most important being those for 1975, 1978 and 1981. In mm of runoff the models indicate either an increase in 1978 of 0.8 mm (model 1) or a decrease of 1 mm (model 2). Model 2 also sets Wellbucket runoff to less than zero when Yarra has an output to input of less than about 0.4%. This results in apparent increases in Wellbucket runoff of over 0.9 mm in the dry years of 1977, 1979 and 1980. In comparison model 1 indicates increases of less than 0.11 mm for these three years. Model 2 also significantly over-predicts 1975 (2.1 mm) and for these reasons model 1 is considered the more useful for determining changes in runoff.

Using model 1, Wellbucket runoff has increased by 0.97 mm on average with a range of 0.04 mm in 1977 to 3.85 mm in 1981. The yield increases in 1975 and 1981 are about 1.5 and 3.4 times what would have occurred before logging.

The average Yarra water output/input over the eight years was 0.85% with a standard deviation of 0.86%. Using equation 5 (model 1) this gives a pre-logging response for Wellbucket of 0.13% which for an annual rainfall of 700 mm produces 0.9 mm of runoff. If the apparent increase due to logging for 1978 and 1981 apply (note higher Yarra 1978 and 1981 average of 1.2%), then additional runoff of between 1.5 mm and 3.0 mm may occur.



Wellbucket - Yarra Runoff Relationship

FIGURE 10

3.4.2 Duration of Streamflow

The duration of streamflow for Wellbucket and Yarra is shown in Figure 11. The three year pre-logging correlation is:-

$$W = -32 + 1.23Y \tag{7}$$

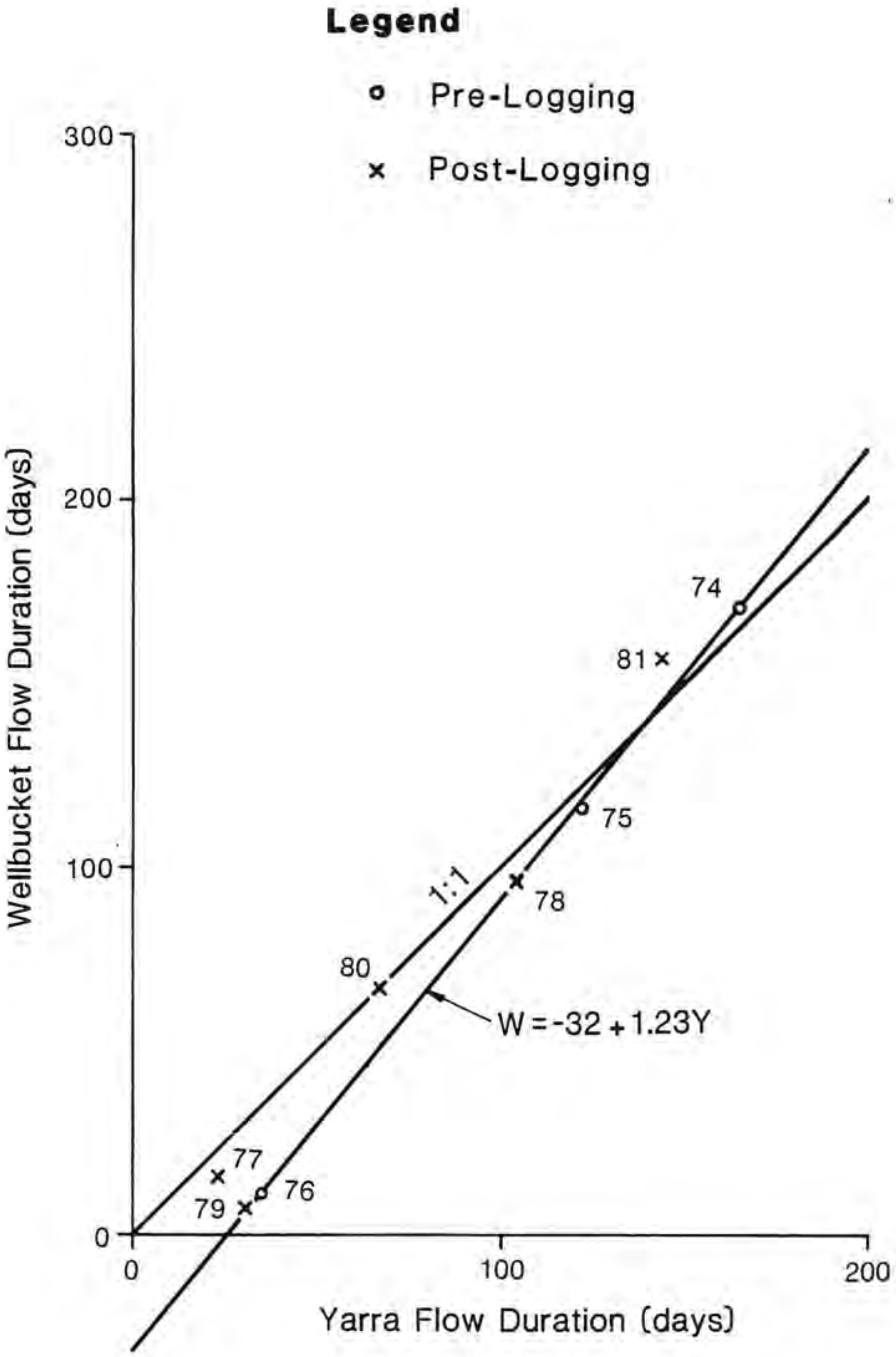
where W and Y are Wellbucket and Yarra flow durations in days respectively.

This equation yields changes in the length of flow from Wellbucket since logging of 20, -1, 3, 17 and 12 days between 1977 and 1981. On this basis streamflow durations have increased by 10 days on average and by less than three weeks in any one year.

3.4.3 Stream Chloride

Yearly flow-weighted streamflow chloride concentrations range from 17 to 40 mg L^{-1}. These concentrations are similar to those of the seasonal, near-surface, perched groundwaters and are much less than those of the permanent groundwaters deeper in the profile (Batini et al., 1977).

The 32 mg L^{-1} concentration for Wellbucket in 1981/82 was about 50% higher than other years and may be a consequence of the logging. However the stream salinity is still very low and therefore logging has not produced a significant deterioration of water quality.



Wellbucket and Yarra Streamflow Durations

FIGURE 11

4. REGIONAL SIGNIFICANCE

4.1 Representativeness of Catchments

The experimental catchments were selected to be generally representative of the eastern Helena catchment in which logging was likely to occur. Extrapolation of the observed hydrological responses to the region is instructive in order to determine the possible significance of a heavy logging operation on water resources.

Wellbucket and Yarra catchments are situated approximately in the middle of the Helena catchment between the 550 mm and 900 mm isohyets (Figure 1). Streamflow from this area is monitored at two gauging stations, Darkin River at Pine Plantation (616 002) and Helena at Poison Lease (616 216), with a combined catchment area of 1284 km^2, which is 87% of the area at Mundaring Weir.

A summary of the landforms and soils for the two catchments is presented in Table 7 (Public Works Department, 1984). These areas were calculated from maps from the 'Atlas of Natural Resources : Darling System, Western Australia (Department of Conservation and Environment, 1980).

Also included in Table 7 is a summary of the approximate percentage of each of the regional landform/soil/vegetation complex in Wellbucket and Yarra catchments. These were produced from Table 1 by combining the first and third types to form the Goonaping/Swamp complex and the fourth, fifth and sixth to form the Dwellingup/Yalanbee complex.

Relative to the larger catchments Wellbucket and Yarra have proportionally more of the upland Dwellingup/Yalanbee complex, significantly less of the Pindalup/Yarragil/Coolakin upland valleys and much more of the Goonaping/Swamp complex. In hydrologic terms this indicates that Wellbucket and Yarra might yield more runoff per unit area because of the higher swamp proportion. However this is offset by the higher proportion of upland complex which is unlikely to produce streamflow. The experimental catchments also lack the Murray Incised Valley complex of the larger catchments which is much more likely to generate runoff due to the steep slopes and shallow soils.

TABLE 7

CATCHMENT LANDFORMS

PROPORTION OF CATCHMENT (%)						
MAP UNITS	Station: Area (km^2)	Darkin 663	Helena 585	Darkin Helena 1284	Well-bucket 4.65	Yarra 6.28
Dwellingup/Yalanbee Laterite Plateau: uplands, duricrust, gravels and sands over mottled clay soils		25	30	27	47	61
Pindalup/Yarragil/Coolakin Upland Valleys: gentle slopes of gravelly duplex soils and sands, some orange earths on valley floor		50	40	45	11	4
Goonaping/Swamp complex: upland depressions, grey sands over clays, swamps		15	5	11	42	35
Murray Incised Valley: moderate slopes, shallow red and yellow earths, alluvium in valley			10	25	17	-

<u>Notes</u>: Darkin River at Pine Plantation (616 002)
Helena at Poison Lease (616 216)
Wellbucket (616 017)
Yarra (616 018)

4.2 Regional Streamflow

The two large catchments upstream of the reservoir, Darkin and Helena, have been gauged since 1968 and 1966 respectively. The mean runoff and the 10%, 50% and 90% (log-normal) probability of non-exceedance of runoff were calculated and are listed in Table 8 with some of the statistics for Wellbucket and Yarra.

Within the region, the runoff from the Helena catchment of 585 km^2 is 1.5 to 2 times that, on average, of the Darkin catchment of 663 km^2. There are probably many reasons for this but an important one may be that the Helena catchment has 146 km^2 compared to 66 km^2 of the Murray Incised valley landform (Table 7) and also has almost twice as much clearing (58 km^2 versus 33 km^2).

This proportion of the clearing may also account for the difference in average yearly flow-weighted salinities of 1300 mg L^{-1} and 400 mg L^{-1} TSS for the Helena and Darkin catchments respectively (Public Works, 1984) and is consistant with the trends reported by Batini and Selkirk (1978).

Runoff from Wellbucket is clearly much less than for the region generally and is also more variable (ratio of mean to median). The rainfall-runoff proportion from Yarra is approximately half that for the region.

Runoff from Wellbucket and Yarra is probably less than the region average because of a lower annual rainfall and because of the absence of the more efficient runoff-producing Murray landform.

4.3 Additional Water Yield

The apparent increased runoff from Wellbucket in 1978 and 1981 (wetter than average winter) ranged from 0.2% to 0.4% of rainfall. For an average rainfall of 700 mm this represents an additional 1.5 to 3.0 mm of runoff (1500 to 3000 m^3 per km^2).

Applying this increase to a nominal 1000 km^2 (excluding the Murray landform) upstream of the gauging stations on the Darkin and Helena rivers (616 002 and 616 216; Figure 1) produces an additional 1.5-3.0 x 10^6 m^3 streamflow in average and wetter years. This potential increase is significant relative to the current average streamflow from those gauged catchments of 8.7 x 10^6 m^3 or 7 mm of runoff (Table 8).

TABLE 8

REGIONAL WATER YIELD STATISTICS

Probability of Non-exceedance (%)	GAUGING STATIONS				
	D (mm)	H (mm)	D + H (mm)	W (mm)	Y (mm)
10	0.4	1.6	1.3	NA	NA
50	6.0	11.0	7.0	0.5	3.0
90	23.0	36.0	23.0	NA	NA
Mean	9.2	13.9	11.0	2.7	6.8

Notes: (i) NA : not available because only 8 data points

(ii) W,Y : Wellbucket and Yarra
D : Darkin River at Pine Plantation
H : Helena at Poison Lease

5. DISCUSSION AND CONCLUSION

5.1 Experimental Results

The study aim was to determine the effects of logging on the response of groundwater and streamflow in a lower rainfall catchment in the Northern Darling Range. In particular, the initiation or increase in the discharge of saline groundwater to streamflow was of concern.

The results indicated very little effect on response of the deeper groundwater and small increases in the amount and duration of streamflow. There was no evidence that the saline groundwaters contributed to streamflow during the experiment. Reasons for these responses can be found by considering the hydrologic system model outlined earlier (Figure 5).

A relatively large unsaturated soil water storage exists in these catchments because of the depth to permanent groundwater, the six months over summer with little rain and the evergreen, deep-rooted vegetation. Soil water storage was not monitored in this study so that changes in this component of the water balance (equation 2) are not known. Sharma (1984) found yearly soil water changes of up to 450 mm (to 6m depth) on a freely-draining site elsewhere in the south west. Therefore a soil water storage of this size (or greater because of the depths to groundwater) on Wellbucket and Yarra would accommodate the greater part of the 80% (560mm) of average rainfall (700 mm) occurring between May and October.

Evaporation of rain intercepted by foliage could also account for a large part of the rainfall during the May to October period (Sharma, 1984). During the experiment evapotranspiration was estimated to account for more than 97.5% of rainfall. Even during the wettest years actual evapotranspiration was only about 50% of pan evaporation. Thus there is a considerable potential for transpiration of additional soil water resulting from thinning such as occurs with logging.

Transpiration is a function of leaf area, stomatal response, soil water availability and weather conditions. In the Northern Darling Range, in the area of the experiment, transpiration would appear to be limited by the availability of water rather than the availability of energy (as evidenced by pan evaporation). A reduction in leaf area by logging might result in a temporary reduction in evapotranspiration and therefore increase in runoff, soil water storage and recharge to the deeper groundwaters.

This effect is likely to be small and transient because the remaining vegetation (including virtually all of the understorey) will respond to the increased supply of water and light by increasing leaf area and evapotranspiration. Regrowth from coppice and seedlings would also have reduced any excess of soil water. In addition only 7% of the stems of the 10-30 cm diameter class were logged (Figure 6). Therefore these smaller, younger trees might be expected to respond quickly with additional leaf area and water consumption.

Loh and Stokes (1981) estimated recharge to groundwaters to be only 5% of rainfall for fully cleared areas in similar rainfall zones in the south west. Since Wellbucket catchment was only selectively logged, any additional recharge to the deeper groundwaters should be less than 35 mm (5% of 700 mm). For a storage coefficient of 0.04 (Bestow, 1976), 35 mm would mean a seasonal water level increase of 0.9 m. Water level increases were less than this in Wellbucket.

The small absolute increases in streamflow quantity and duration can be best attributed to the observation that the generation of streamflow occurs through:-

(i) perched groundwaters draining from the side slopes into the valley and swamps and thence to the streamline. The response of this system is dampened because of transmission through the shallow soils and it contributes mainly to the sustained stream base flow.

(ii) the swamps saturate due to the input from both rainfall and seepage from the perched groundwaters upslope and form a virtually impervious area. Subsequent rainfall on this area contributes relatively quickly to form the stream 'storm-flow' hydrograph.

Increases in the amount and duration of runoff may have resulted from reduced evapotranspiration (due to logging) on the valley sideslopes producing more perched groundwaters and hence more and longer duration seepage into the swamp. (The swamp area on Wellbucket was little affected by the logging operation as there was no timber worth cutting in this area.) A larger or more sustained area of saturated swamp on Wellbucket could easily account for the additional runoff, from direct rainfall, without the remainder of the catchment contributing.

5.2 Regional Implications

The streamflow and groundwater responses from the logging on Wellbucket catchment indicate that a similar logging operation through the eastern Helena catchment would not result in a deterioration in stream water quality. This result and validity of application to the region is dependent upon the variation in depths to the permanent, saline groundwaters across the region. Where those depths are at least greater than 5m a Wellbucket type of logging can be expected to have little if any permanent effect on the deeper groundwaters and hence stream water quality because vigorous regrowth should ensure a return to a pre-logging water balance within 5 to 10 years.

The possible streamflow increase of 1.5-3.0 x 10^6 m^3 from a regional logging operation is also likely to be transient as the regrowth restores the water balance. The increase is also not very significant relative to the Mundaring Reservoir (storage capacity 77 x 10^6 m^3) system yield of about 30 x 10^6 m^3.

Therefore for such small benefits relative to possible silvicultural management costs, resources may be better utilized in the higher rainfall areas where larger increases in runoff can be expected as suggested by Shea et al. (1978). For Mundaring Reservoir this would be in areas of greater than 900 mm average rainfall. However, as noted by Loh and Stokes (1981), groundwaters are closer to ground level in these areas and may contribute to streamflow if disturbed by logging, resulting in a deterioration in stream water quality.

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APPENDIX 1

Vegetative indicator species and corresponding code (after Havel 1975a and b)

CODE	INDICATOR SPECIES
A	Swamp areas. Indicator species are Hakea varia and Melaleuca species.
F/J	Yellow Sands. The indicator species are Stirlingia latifolia, Phlebocarya ciliata, Conospermum stoechadis, Baeckea camphorosmae, Mesomelaena tetragona, Eucalyptus marginata and Eucalyptus calophylla.
J	Leached Sands. indicated by the presence of Lygenia tenax, Banksia attenuata, Calytrix angulosa and Scirpus curvifolius in addition to species listed for F/J.
H&P	Are similar and are classified together. The soil is a loamy sand or sand matrix to medium-heavy gravel. Laterite is frequently present. Indicator species are predominant stands of E. marginata with light E. calophylla, Bossiaea ornata, Patersonia rudis, Petrophile striata, Styphelia tenuiflora, Xanthorrhoea gracilis and preissii, Lasiopetalum floribundum and light Hakea lissocarpha.
M	The soil is a loam of sandy loam matrix with gravel or laterite. Indicator species are E. wandoo, E. marginata, E. calophylla, Hakea lissocarpha, Macrozamia reidleii, Petrophile striata and Xanthorrhoea.
Y	The soil is a shallow sand or loam over clay. Indicator species are E. wandoo and E. calophylla, Hypocalymma angustifolio, Mesomelaena tetragona, Baeckea camphorosmae. Where the top layer is sand, indicators of this type are also present. As the shallow soil over clay is the most important criterion these have been grouped.
G	Areas of surface granite rock devoid or sparsely covered by trees with laterite floaters or heavy gravel covering the rock. Indicator species are Hakea undulata, Hakea stenoptera, Dryandra armata and Dryandra sessilis.
M/G, H/G, Y/G	These area have the G type indicators as well as the species of type M, H or Y. They are reasonably shallow soil types.