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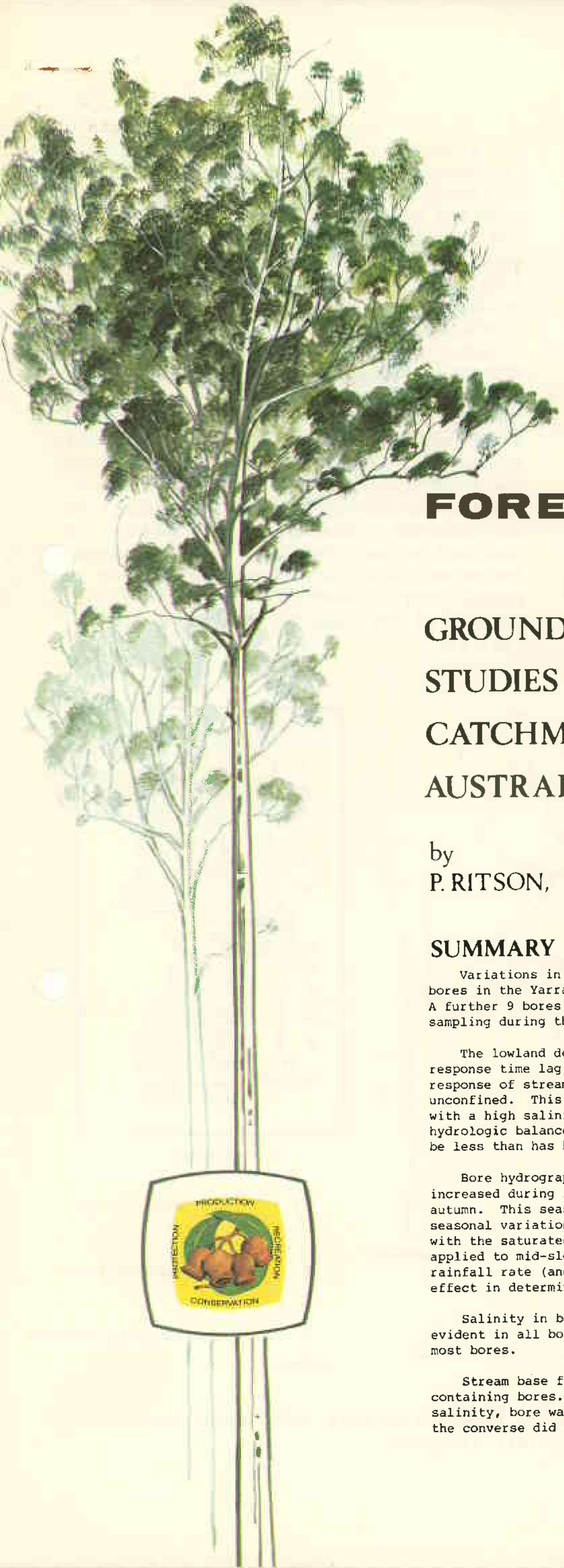

FORESTS DEPARTMENT
OF WESTERN AUSTRALIA

GROUNDWATER HYDROLOGY STUDIES IN THE YARRAGIL CATCHMENT, WESTERN AUSTRALIA

by
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SUMMARY

Variations in groundwater potentiometric head and salinity in 18 bores in the Yarragil Catchment were studied from May 1975 to April 1978. A further 9 bores were either dry or contained insufficient water for sampling during the study period.

The lowland deep aquifers were semi-confined. Therefore, the response time lag between the disturbance of upland forest and the response of stream salinity may be less than if deep aquifers were all unconfined. This has implications for the rehabilitation of catchments with a high salinity hazard. The time available to restore the hydrologic balance to prevent an adverse increase in stream salinity may be less than has been assumed.

Bore hydrographs showed that groundwater potentiometric head increased during late winter and spring and decreased during summer and autumn. This seasonal pattern in valley bores was attributed mainly to seasonal variation in water uptake by plant roots from soils contiguous with the saturated zone. But the results did not show whether the same applied to mid-slope and divide bores or whether seasonal variation in rainfall rate (and therefore groundwater recharge rate) had greater effect in determining the shape of mid-slope and divide bore hydrographs.

Salinity in bores fluctuated widely, with distinct peaks and troughs evident in all bores. There was no obvious seasonal pattern typical of most bores.

Stream base flow salinity was calculated for subcatchments containing bores. In subcatchments with a high stream base flow salinity, bore water salinity (∿ groundwater salinity) was also high but the converse did not always apply.

INRODUCTION

Hydrology of the Yarragil Catchment, which is centrally located in the intermediate rainfall zone of the northern jarrah (*Eucalyptus marginata* Sm.) forest (Fig. 1), has been intensively studied since 1973 as part of broadscale studies of the effect of changes in forest composition and structure on water quality and yield (Shea *et al.*, 1975).

Studies of the groundwater component of the hydrologic cycle commenced in 1975 with the establishment of a network of cored bore holes to determine the distribution of soil salts (Herbert *et al.*, 1978) and to measure groundwater potentiometric head[1] and salinity. The objective was to characterize the groundwater hydrologic regime under native forest so that any changes in stream water quality and yield caused by alterations to the forest could be more easily predicted.

In this paper we cover two aspects of the groundwater studies in Yarragil Catchment. Firstly, we report the variation in groundwater potentiometric head and salinity within and between bores and discuss the results in relation to forest management. Secondly, we describe initial attempts to establish correlations between salt concentrations in catchments (total salt storage per unit area of catchment and groundwater salinity) and stream salinity.

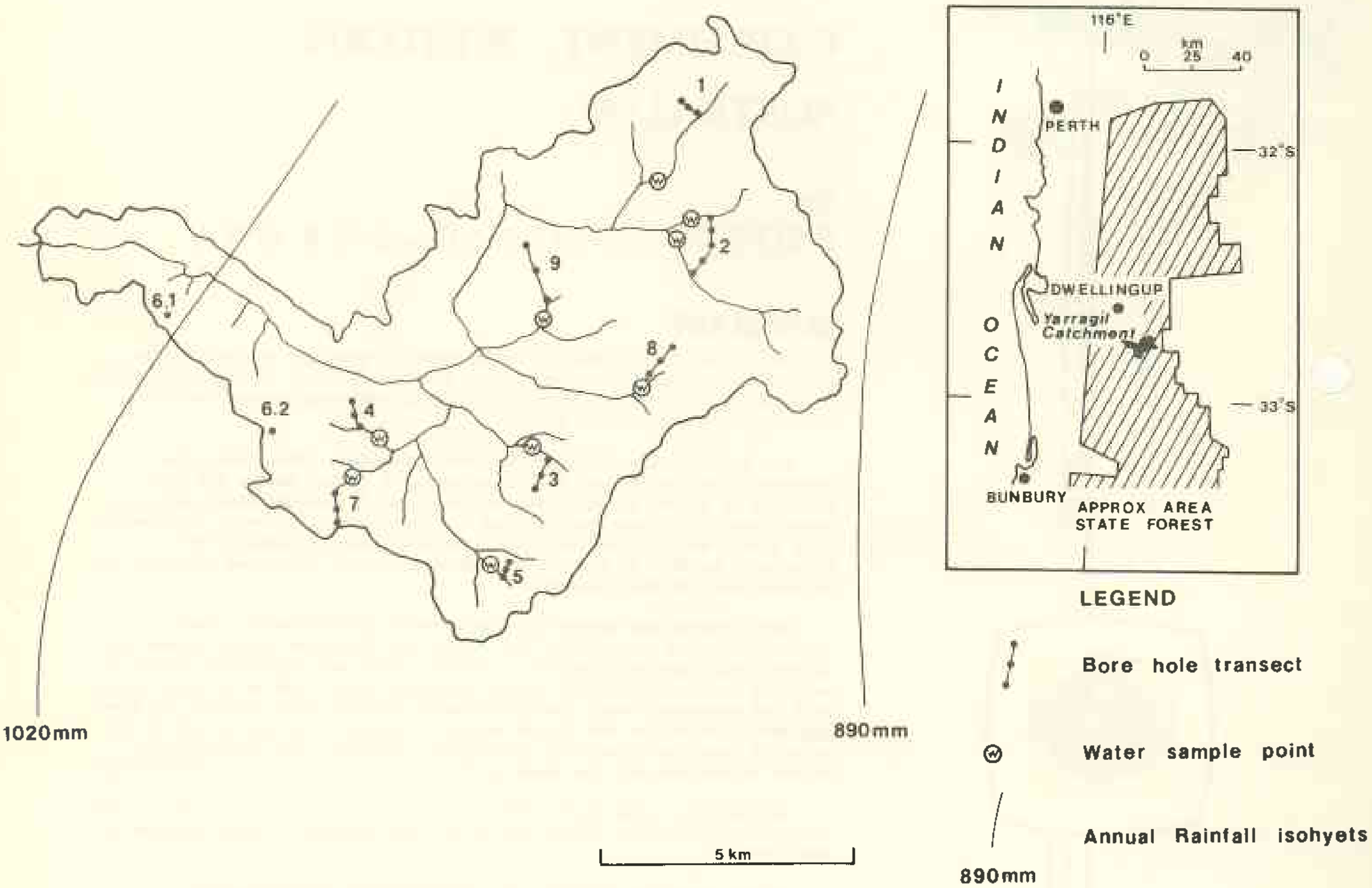

FIGURE 1: Yarragil Catchment showing location of bore hole transects, water sample points and annual rainfall isohyets.

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[1] The potentiometric head is the height to which water will rise in a well penetrating an aquifer. If the aquifer is unconfined, the potentiometric head, the water table and the surface of the zone of saturation all coincide. However, if the aquifer is confined or semi-confined under pressure the water table is not defined and the potentiometric head is located above the surface of the zone of saturation (see Fig. 6).

METHODS

Cored bore holes

Twenty seven cored bore holes were drilled at nine sites in the Catchment (see Fig. 1). The sites, the methods of drilling, piezometer emplacement and the method for calculating total soluble salts were described by Herbert *et al.* (1978).

In the bores that contained sufficient water for sampling, groundwater potentiometric head and salinity were monitored monthly from May 1975 to December 1978.

The water level in the bores was measured with an electric probe and was assumed to be groundwater potentiometric head.

Bore water salinity was estimated from the electrical conductivity of bailed samples collected from the top two metres of water (if there was sufficient water) using the equation

$$y = -36.52 + 7.05 \ \chi$$

where y is the salinity in mg. L^{-1} total dissolved solids (TDS) and χ is the electrical conductivity of the water sample at 25°C in mS.m^{-1} (Hatch, 1976).

Stream base flow salinity

Stream salinity was measured weekly from 1974 to 1978 at 48 sites in the Yarragil Catchment. Base flow salinity was calculated as the mean of the last three weekly salinity readings taken prior to cessation of streamflow.

Regression Analysis

Regression analysis was carried out on paired data of:

(1) stream base flow salinity[1] (χ) and mean bore water salinity for a subcatchment[2] (y)

(2) mean bore water salinity[3] (χ) and total salt storage[4] (y),

and in both cases regression curves of y on χ, $\ell n\ y$ on χ, y on $\ell n\ \chi$ and $\ell n\ y$ on $\ell n\ \chi$ were calculated.

RESULTS and DISCUSSION

Dry bores

One third of the bore holes were either dry (holes 1.3, 3.3, 4.3, 6.1, 7.3, 9.2, and 9.3) or contained insufficient water for sampling (holes 4.2 and 6.2) during the study period.

All of the dry bores were located in divide or mid-slope positions. They indicate sites where there was no water table (saturated zone) during the study period. However, ephemeral water tables may form at these sites during periods of above-average rainfall. Simple salt balance calculations indicate that there must have been at some time(s) an output of salt in lateral flows from the sites of the dry bores either in ephemeral water tables or in unsaturated flow. If there were no output of salt, the salts stored in the soil could have accumulated in less than 1000 years at holes 6.1, 7.3 and 9.2 and less than 5000 years at holes 1.3, 3.3, 4.3 and 9.3. (Estimates were based on calculations of salt fall by Hingston and Gailitis (1976) and of salt storage by Herbert *et al*,(1978)). It seems reasonable to assume that salt has been accumulating for longer periods.

Aquifer confinement

It is apparent from the bore hydrographs (Fig. 2) that the lowland deep aquifers were semi-confined under pressure.

Firstly, the groundwater potentiometric head in three valley bores (2.1, 3.1 and 9.1) rose above the land surface during the study period, providing direct evidence of aquifer confinement.

Secondly, Fig. 2 shows the initial groundwater potentiometric head in all bores was higher than the surface of the saturated zone recorded at the time of drilling. Differences were greatest in valley bores (range 6.5 to 2.5 m) and least in divide bores (range 1.4 to 0.4 m). This indicates that valley bores intersected deep aquifers semi-confined under pressure and that some mid-slope bores also

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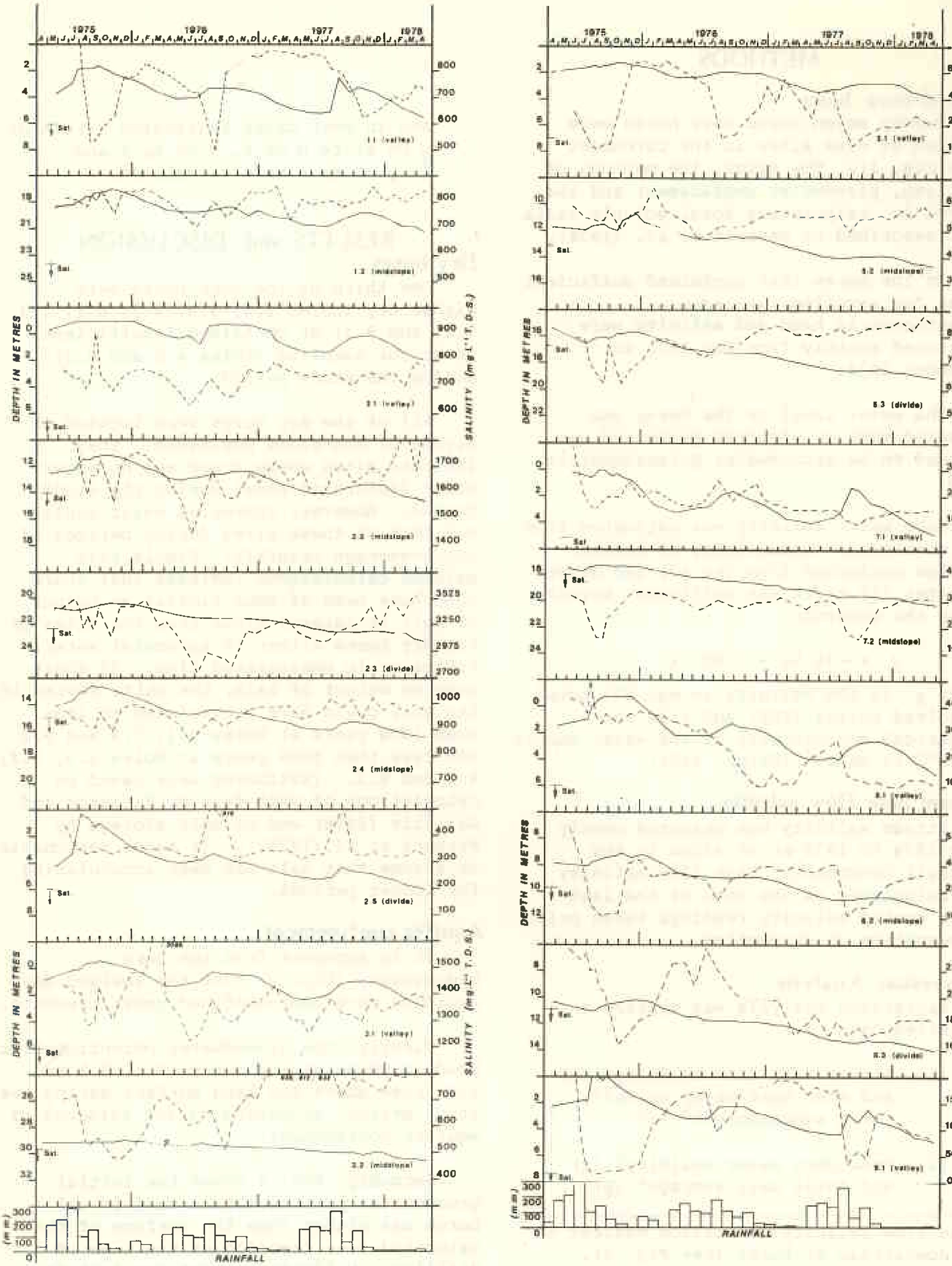
[1] Base flow salinity at station nearest to and downstream of bores (see Fig. 1).

[2] Mean of mean bore water salinities of bores in subcatchment.

[3] Mean of monthly determinations.

[4] Calculated from soil cores, methods described by Herbert *et al.*(1978).



——— depth of groundwater potentiometric head below land surface (metres)

------ bore water salinity (mg.L^{-1} TDS)

$\overset{\top}{\downarrow}$ surface of saturated zone at time of drilling

FIGURE 2: Variation in bore water level and salinity with time and monthly rainfall.

intersected deep aquifers which were semi-confined, but under less pressure. The comparatively small differences between the initial groundwater potentiometric head and the surface of the saturated zone recorded in the divide bores indicates some deep aquifer confinement. This is possible as the divide bores intersected deep aquifers which had possible recharge areas upslope along the line of the divide. However, the recorded differences may have been due to errors in determining the exact surface of the saturated zone.

Further evidence of aquifer confinement is apparent from comparisons of groundwater potentiometric head with the vertical patterns of salt distribution obtained from analysis of cores collected while constructing the bore holes. These core data have been described by Herbert *et al.* (1978), who found that a "salt bulge" (accumulation of salt) was common above the saturated zone. Figure 3 shows a typical profile with a salt bulge between 6 and 12 metres. We consider the comparatively uniform distribution of salt below the salt bulge to be due to dispersion of salts in the groundwater. Provided there has been no major recent forest disturbance (and therefore a recent increased recharge to the deep aquifer due to a reduction in evapotranspiration losses), the location of the groundwater potentiometric head within or above the salt bulge would indicate a semi-confined aquifer. Only at site 2.5 has there been any major recent forest disturbance, yet in all of the valley bores the groundwater potentiometric head rose above the salt bulge during the study period. In three of the mid-slope sites (1.2, 2.2 and 8.2) the groundwater potentiometric head rose to within the salt bulge but in all other sites groundwater potentiometric head remained below it.

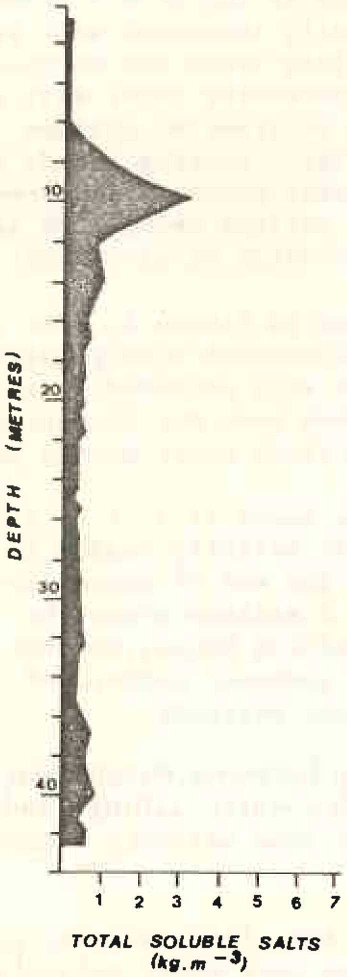


FIGURE 3: Vertical distribution of salt in bore hole 2.2. Note the "salt bulge" between 6 and 12 m depth.

Semi-confined lowland deep aquifers may be confined below by bedrock, but it is not clear what constitutes the upper confining layer. Bettenay *et al.* (1964) concluded that semi-confined aquifers of pallid zone clay in the Belka Valley, inland of the northern jarrah forest, were confined above by an aquiclude of either massive clays or hardened, mottled zone material (cap rock). Similar aquicludes may constitute the upper confining layer of semi-confined aquifers in the northern jarrah forest.

Seasonal variation in groundwater potentiometric head

All of the bores showed a net decline in groundwater potentiometric head during the study period (see Fig. 2). We attribute this to a decline in rainfall from above average in 1973 and 1974 to below average during each year of the study period (1975 to 1978).

Superimposed on the trend of a net decline, the bore hydrographs (see Fig. 2) also show a general increase in groundwater potentiometric head in late winter and spring followed by a decline in summer and autumn. This pattern could be explained by seasonal variation of either discharge from, or recharge to, the groundwater.

Discharge from the groundwater could vary with the rate of water uptake by plant roots from the soil contiguous with the groundwater. Studies of the water relations of jarrah by Grieve (1956) and Doley (1967) indicate that jarrah is a prodigious water user which maintains or increases transpiration rates from spring into summer despite a considerable decline in surface soil moisture during this period. Water uptake by jarrah roots from deep in the soil would therefore be greatest in summer (i.e. when groundwater potentiometric head in bores falls) and least in winter (i.e. when groundwater potentiometric head in bores rises). The conclusion that jarrah is capable of withdrawing water from deep in the soil was confirmed by Kimber's (1974) observations of jarrah roots in bauxite mine pit faces and soil excavation trenches.

However, data presented by Williamson and Bettenay (1979) show that if forest cover in a catchment is replaced by shallow rooted grasses the response of groundwater potentiometric head in deep bores may still show distinct seasonal rises and falls. This indicates a response of groundwater potentiometric head to seasonal variation in rainfall (and therefore soil water recharge).

There was a time lag between maximum rainfall (winter months) and the period when the groundwater potentiometric head in the bores rose (see Fig. 2). The time lags, calculated from bores with a pronounced seasonal rise and fall in groundwater potentiometric head, were generally less than two months, the average time lag being less than one month.

Time lags of similar duration have been recorded in other studies in the northern jarrah forest. There is evidence that this rapid response to rainfall of groundwater potentiometric head in some bores may be due to rapid downward movement of water in root channels (D. Hurle , personal communication).

However, if lowland deep aquifers are semi-confined under pressure, vertical downward recharge to lowland deep aquifers via root channels would not be possible. Recharge must occur by lateral flow from upslope. Thus, valley bores would have responded to seasonal recharge after mid-slope bores. But groundwater potentiometric head rose and fell at about the same time in valley bores and mid-slope bores. This indicates that discharge due to water uptake by plant roots was more important than variation in recharge rate in determining the shape of valley bore hydrographs. Our data do not show which of the two processes (discharge or recharge) were of greater effect in determining the shape of mid-slope and divide bore hydrographs.

Groundwater salinity

Water samples were collected from the bores to obtain representative samples of groundwater. However, piezometers were slitted to above the saturated zone and, where deep aquifers were semi-confined, water levels in bores would have been above the saturated zone. Therefore, salts stored above the saturated zone could have been leached into the bores and it may not be reasonable to assume that the salinity of bailed samples was representative of groundwater salinity. For this reason results are quoted as bore water salinity and not groundwater salinity.

Table 1 shows that, with the exception of the bores in the site 3 transect, bore water salinity increased with progression upslope. This trend was matched by a trend of increasing total salt storage in soils with progression upslope (Herbert *et al.*, 1978). Reverse trends have been found in other parts of south-western Australia, valleys being more saline than uplands (Johnston *et al.*, 1980).

As shown in Figure 2, bore water salinity fluctuated widely: distinct peaks and troughs were recorded in all bores. This may have been due to patches of saline and fresh water moving past bores.

In some bores (1.1, 2.2, 2.3, 3.1, 5.1 and 5.2) salinity tended to be at a maximum at the end of summer (February/ March) and a minimum after the winter rains. In the remaining bores, however, there was no obvious seasonal pattern of variation in bore water salinity.

Relationship between stream base flow salinity, bore water salinity and total storag

Stream base flow salinity v bore water salinity

. Stream base flow salinity plotted against mean bore water salinity (Fig. 4) shows that mean bore water salinity in each subcatchment was either greater than or nearly equal to stream base flow salinity

TABLE 1

Bore water salinity and total salt storage

Borehole No	Topographic location	Mean bore water salinity (mg.L^{-1}T.D.S.)[1]	Mean bore water salinity for subcatchment (mg.L^{-1}T.D.S.)[1]	Salt storage (kg.m^{-2}T.D.S.)	Mean salt storage for subcatchment (kg.m^{-2}T.D.S.)	Stream base flow salinity (mg.L^{-1}T.D.S.)
1.1	Valley	721	765	6.3	7.5	666
1.2	Mid-slope	809		8.7	-	-
2.1	Valley	745		8.9	-	-
2.2	Mid-slope	1691	1824[2]	24.7	25.1[2]	780
2.3	Divide	3035		41.6	-	-
2.4	Mid-slope	971	1452[3]	25.6	24.3[3]	259
2.5	Valley	351		5.7	-	-
3.1	Valley	1350	1052	10.1	24.5	795
3.2	Mid-slope	754		38.9	-	-
5.1	Valley	336		14.2	-	-
5.2	Mid-slope	529	564	33.9	22.9	416
5.3	Divide	828		20.5	-	-
7.1	Valley	144	205	4.1	6.5	230
7.2	Mid-slope	266		8.9	-	-
8.1	Valley	127		5.4	-	-
8.2	Mid-slope	269	736	7.3	9.5	860
8.3	Divide	1812		15.7	-	-
9.1	Valley	1064	1064	30.0	30.0	657

NOTE: Only data from bores which contained sufficient water for sampling are included in this table.

[1] Mean of monthly salinity determinations
[2] Mean, Holes 2.1, 2.2 and 2.3
[3] Mean, Holes 2.3, 2.4, and 2.5

calculated for the same subcatchment. This indicates that, if stream base flow salinity is high, bore water salinity (and therefore groundwater salinity) will also be high. However, the data in Figure 4 also show that the converse may not apply.

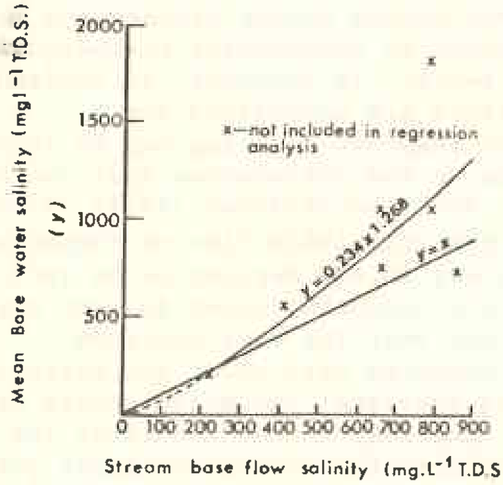


FIGURE 4: Stream base flow salinity vs mean bore water salinity.

Of the four regression curves calculated, the regression curve of $\ell n\ y$ on $\ell n\ x$ gave the best fit (r = 0.88). With one point excluded from the analysis, the regression equation calculated was $y = 0.234\ x^{1.268}$. We consider that the point excluded from the regression analysis represents data obtained from a subcatchment where groundwater does not contribute significantly to streamflow.

More data are needed before we can attempt to establish a regression curve that could reasonably be used to predict groundwater salinity from stream base flow salinity. Even then, gross errors in prediction could result if the curve were applied to areas where groundwater does not contribute significantly to streamflow. This appears to be common in undisturbed low rainfall (<1000 mm per annum) areas of the Darling Range.

La Sala (1967) and Pinder and Jones (1969) used stream base flow salinity to estimate groundwater salinity in some North American catchments. However, if we assume that stream base flow salinity is equal to groundwater salinity ($y = x$ in Fig. 4) we would tend to underestimate ground water salinity and the underestimate would increase with increasing groundwater salinity.

Bore water salinity v total salt storage

Mean bore water salinity is plotted against total salt storage in Figure 5. Of the four regression curves calculated, the regression curve of $\ell n\, y$ on $\ell n\, x$ gave the best fit (r=0.68). The regression equation calculated was $y = 0.156x^{0 \cdot 686}$. Variation from the calculated regression curve tended to increase with increasing salinity. Hence, use of the regression curve to predict total salt storage from bore water salinity could lead to gross errors. Even greater errors may result if the same method of prediction were applied to areas outside the Yarragil Catchment.

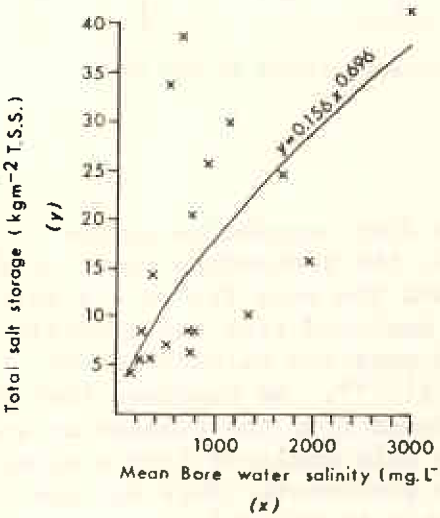


FIGURE 5: Mean bore water salinity vs total salt storage.

MANAGEMENT IMPLICATIONS

Assessment of the salinity hazard

An assessment of salinity hazard is necessary in the formulation of management plans to optimize the yield of acceptable quality water from jarrah forest catchments. Where the salinity hazard is low it may be desirable to thin the forest to increase water yield. Conversely, where the salinity hazard is high it is important to maintain full forest cover (Shea, *et al.*, 1975).

The salinity hazard of a catchment will depend on *salt concentration* in the soil and the *response time lag* between forest disturbance and change in stream salinity.

Salt concentration

We were not able to use stream base flow salinity to determine a general relationship that could be used to reliably predict salt concentration in jarrah forest catchments. However, the analysis did indicate that catchments with a high stream base flow salinity contain areas with high salt concentrations. This information on small (first order) catchments may be sufficient for some management and land-use decisions. However, if base flow salinity is low, more work to determine salt concentration in the catchment may be necessary. At present the only reliable method to determine salt concentration in catchments is by the highly expensive procedures of drilling and analysis of soil cores and measurement of groundwater salinity in bores.

Response time lags

Aquifer confinement may have an important effect on response time lags. Results of this study show that, in the Yarragil Catchment, lowland deep aquifers are semi-confined. In this case, the effect of an increase in recharge to the upland unconfined part of a deep aquifer may be rapidly transmitted to the lowland semi-confined part of the deep aquifer as an increase in pressure which will increase the rate of vertical discharge of groundwater (Fig. 6). As groundwaters in jarrah forest catchments are generally more saline than stream waters, stream salinity will increase. The response time lag between upland forest disturbance and increases in groundwater discharge may be quite short. In contrast, if lowland deep aquifers are unconfined the equivalent response time lag may be longer. As a guide to the differences that can be expected, Peck and Bettenay (1976) calculated that the characteristic time of response of deep aquifers in the Darling Range (which includes the northern jarrah forest) may be about one year for semi-confined aquifers compared with about ten years for unconfined aquifers. No measurements of response time lags in catchments of the northern jarrah forest are available yet.

Rehabilitation of disturbed forest

Maintenance of potable water in fresh streams in undisturbed jarrah forest catchments, despite the presence of high

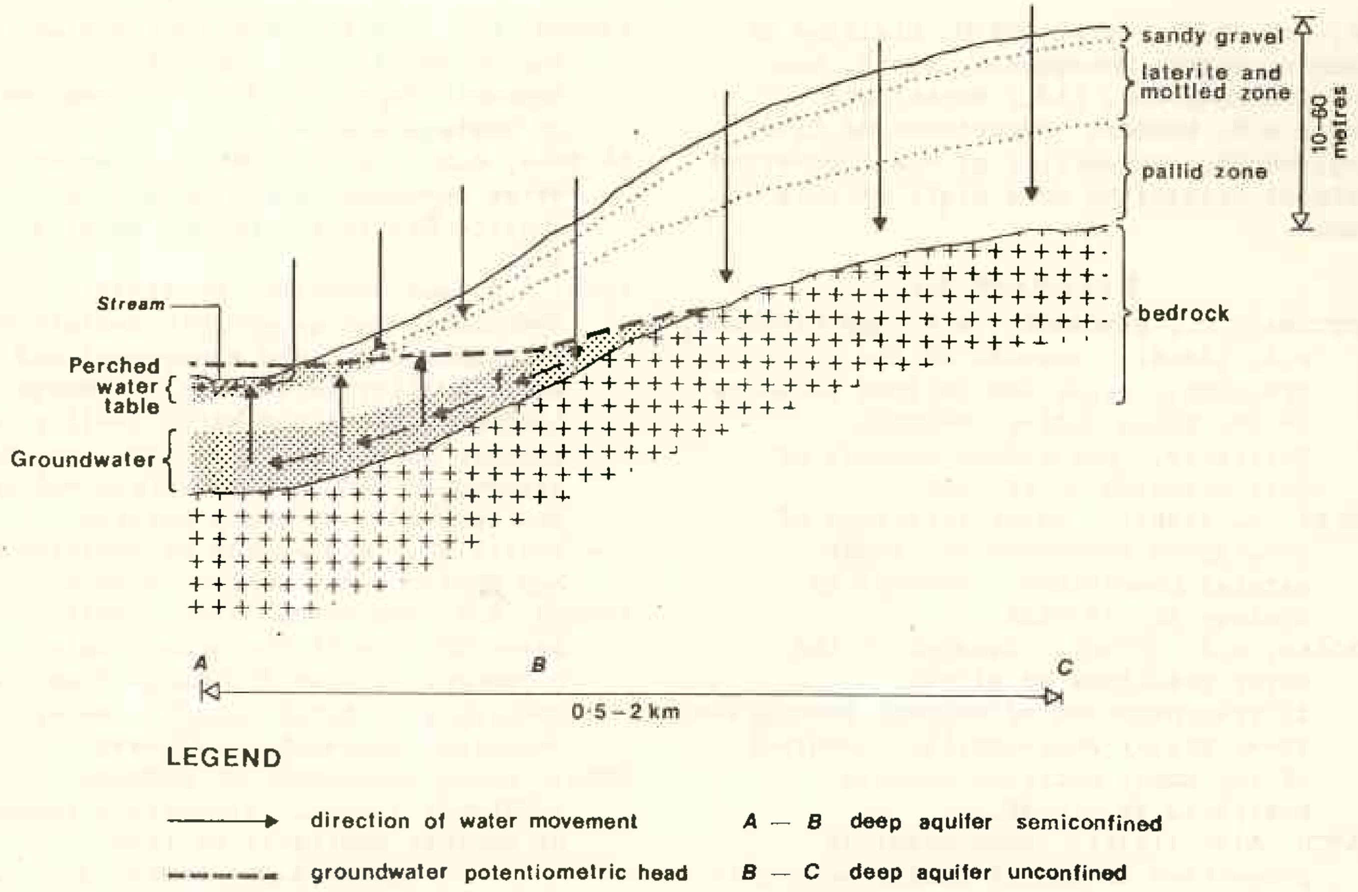


FIGURE 6: Model of water movement in typical northern jarrah forest soil. Water uptake by plants is not shown. The deep aquifer consists of the middle and lower portion of the pallid zone.

concentrations of salt in the soil and subsoil, is dependent on the capacity of the native vegetation to transpire a large proportion of rainfall. (Analysis of data presented by Public Works Department of Western Australia (1975) shows that evapotranspiration from fully forested catchments of the northern jarrah forest may be as high as 1100 $mm.yr^{-1}$ and amounts to between 85 and 97% of the rainfall).

To reverse any adverse trend caused by an increase in stream salinisation, replacement vegetation would need the capacity to duplicate the high transpiration rates of the original jarrah forest. If lowland deep aquifers are semi-confined so that the response time lag between disturbance and an increase in stream salinity is short, then the time available for replacement vegetation to restore the balance may also be short.

If a system of root channels allows rapid recharge to deep aquifers in the upland (mid-slope and divide) areas of a catchment, replacement vegetation may also need the capacity to develop a deep root system. It is theoretically possible for shallow rooted vegetation to transpire a high proportion of rainfall. However, water entering the soil may effectively bypass the shallow roots by rapid transmission to deep in the soil via old root channels formed prior to any forest disturbance. Only deep-rooted vegetation could draw on this water.

It follows that replacement vegetation used to rehabilitate disturbed upland jarrah forest in catchments with a high salinity hazard may need the capacity to rapidly develop both a deep root system and a canopy dense enough to transpire at the rate of the original forest.

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