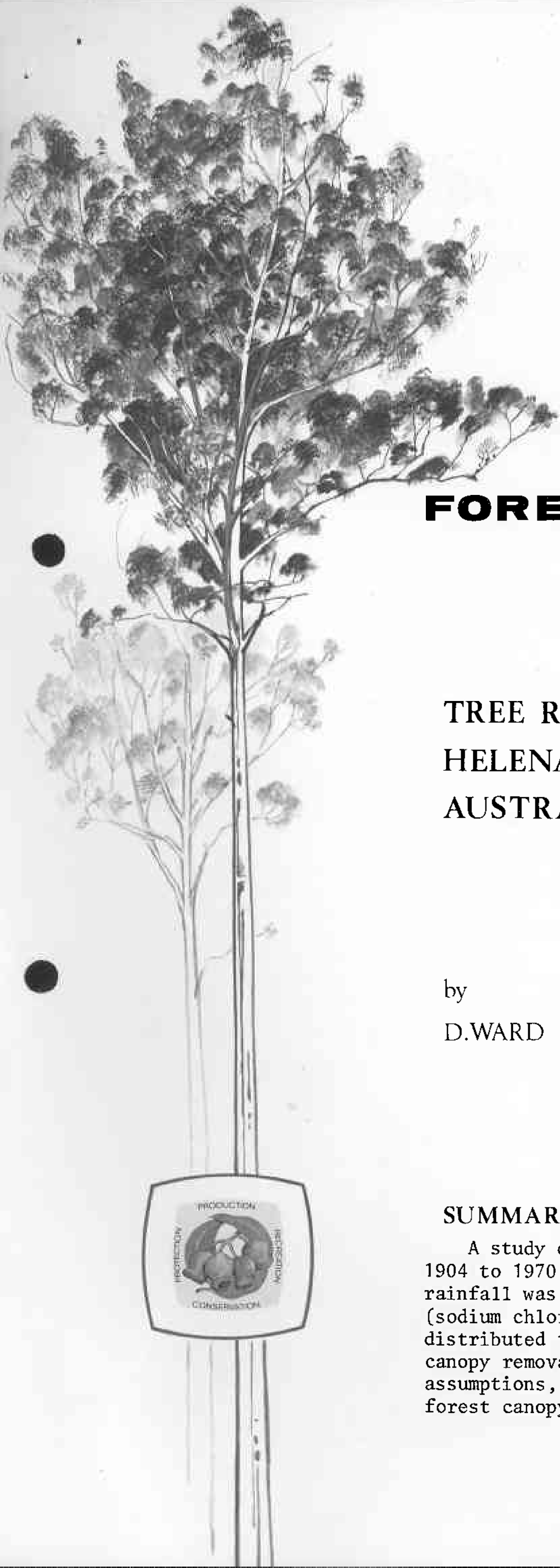

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FORESTS DEPARTMENT
OF WESTERN AUSTRALIA

TREE REMOVAL AND SALINITY IN HELENA CATCHMENT, WESTERN AUSTRALIA

by

D.WARD

SUMMARY

A study of the records of Helena Catchment from 1904 to 1970 showed that when noise due to varying rainfall was mathematically removed, annual saltflow (sodium chloride) into the dam was not randomly distributed through time. When the record of forest canopy removal was modelled according to certain assumptions, a strong correlation was found between forest canopy removal and saltflow.

INTRODUCTION

A possible link between removal of native vegetation and increasing stream salinity in Western Australia was proposed by Wood in 1924. A more recent survey was made by Peck and Hurle (1973). The following records of Helena Catchment from 1904 to 1970 were examined to investigate the relationship between removal of native vegetation and stream salinity: weather (from the Commonwealth Meteorological Bureau), cutting and clearing (from the Forests Department of Western Australia), and dam levels and salinities (from the Public Works Department and the Perth Metropolitan Water Board).

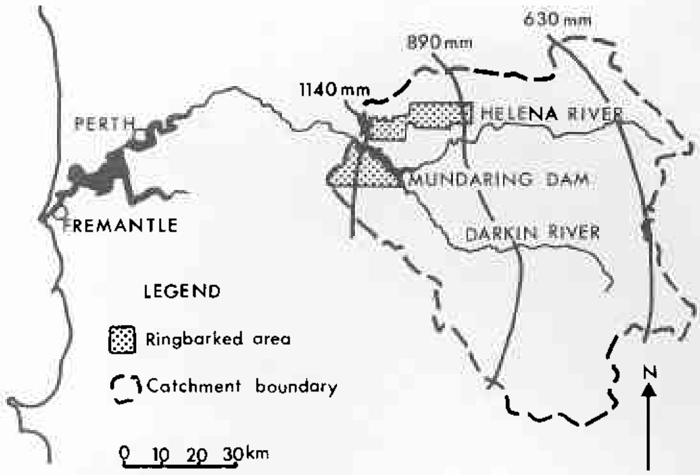

FIGURE 1: Location of Helena Catchment showing Helena and Darkin Rivers, Mundaring Dam, rainfall isohyets, and areas ringbarked.

Description

Helena Catchment covers about 1500 km^2 (Figure 1). In general, the topography is flat in the east but more dissected in the west toward the Darling Scarp. The dam is situated in the high rainfall zone in the valleys of the two main streams, the Helena and Darkin Rivers. It has a capacity of 68.9 $m^3 \times 10^{-6}$ which can be raised to 77.1 $m^3 \times 10^{-6}$ by use of the crest gates. In the west of the Catchment, where jarrah (Eucalyptus marginata Sm.) is the main species, the canopy cover is about 75%. In the east, where wandoo (Eucalyptus wandoo Blakely) is the main species, canopy cover decreases to about 20%.

History

The first major removal of forest canopy in the Catchment was in the first decade of this century, just after the dam wall was completed. Owing to a succession of dry years the dam did not fill, so in about 48 km^2 of the high rainfall zone close to the dam, and in about 18 km^2 of the subcatchment of the Helena River, the trees were killed by ringbarking. This treatment seemed to give more runoff, although the effect was partially masked by a wetter-than-average year (1907). Although the dam filled, some streams in the ringbarked areas were more salty than before, and, as will be shown later, there was a marked rise in the amount of salt flowing into the dam.

Parts of the ringbarked areas were planted with pines in the second and third decades. The Catchment has been logged at varying intensities since 1900, with extensive cutting of green firewood by the Wundowie Iron and Steel Company since 1960. Since 1948 there has been an upsurge of clearing of Private Property for agriculture.

TABLE 1
Method of calculating annual inflow of salt and water for Mundaring Dam

	Weight of salt	Volume of water	Salinity	
Initial	A	*F	*L	(A = F X L)
Inflow	B	G	M	
Rain on surface	C	*H	*N	(C = H X N)
Evaporation from surface	-	*I	-	
Draw	D	*J	*O	(D = J X O)
Spill	E	*K	*P	(E = K X P)
Final	A'	*F'	*L'	(A'= F'X L')

*- known variable

A' = A + B + C - D - E
→ B = A' - A - C + D + E

F' = F + G + H - I - J - K
→ G = F' - F - H + I + J + K

METHOD

Data conversion

The amount of salt (sodium chloride) and water flowing into the dam each year was calculated by a simple book-keeping method from the raw data on dam levels and salinities (Table 1). Salinity of 10 ppm was used for the rainfall at the dam (Hingston, 1958).

There are several complications with the removal of tree canopy.
(1) The canopy cover diminishes from west to east so that the removal of a given percentage of original canopy in the west implies removal of a greater absolute amount of canopy, or transpirational surface, than does removal of the same percentage of original canopy in the east.
(2) Intensity of removal ranges from total removal for agricultural clearing down to removal of 40% of original canopy in the lightest logging.
(3) No record of original canopy over the whole Catchment exists - only recent air-photo interpretation maps after the removal has taken place and some regrowth has occurred.

Consequently, a single variable dubbed Forest Canopy Removal was created which allows for the above considerations according to the Assumption 3 below. To do this, original canopy cover was estimated. From an air-photo interpretation map, areas of prime, mature forest within the Catchment were located. Ten of these were then selected at random, and the percentage canopy cover paired with the annual rainfall for that part of the Catchment. Although the relationship between rainfall and canopy cover is almost certainly sigmoid (since canopy cover cannot be less than 0% nor greater than 100%), for the range of rainfall encountered a linear regression gave a satisfactory fit (Figure 2). From this regression, original canopy covers for the different rainfall zones were estimated.

Assumptions

Before tackling the analysis, the following assumptions were made.
(1) There was little if any canopy removal on the Catchment before this century.
(2) If canopy removal causes salt to be set in motion, then regrowth of trees, while possibly preventing further salt mobilisation, will not stop the movement of that salt already in motion.

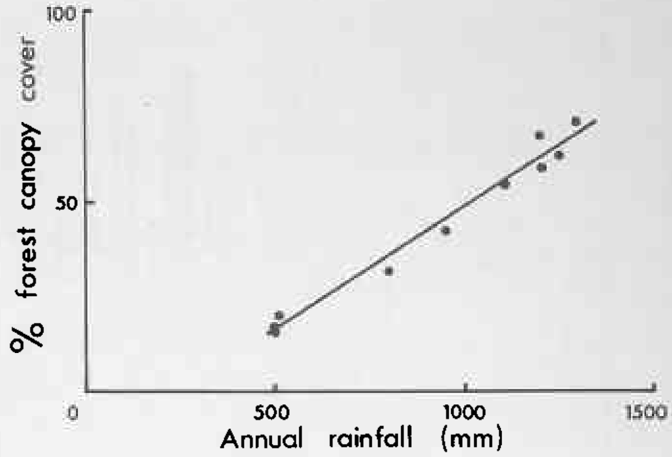

FIGURE 2: Relationship between % forest canopy cover (Y) and annual rainfall (X)
$Y = 0.07X - 16.8$ $r = 0.9897$***
S.E.est. = 3.14
95% C.L.est = $\pm$ 6.15%

(3) A variable which determines evapotranspiration effects is leaf area, and removal of part of the canopy over a large area will reduce evapotranspiration by the same amount as total removal of canopy over a proportionately smaller area. Again, total removal of canopy in heavy forest (high percentage canopy cover) will reduce evapotranspiration by a proportionately greater amount than total removal of canopy in a light forest (low percentage canopy cover). To put it more succinctly:
if Φ is original percentage forest canopy cover,
χ is percentage of original canopy removed,
ψ is total area over which removal took place,
and ω is actual area of tree canopy removed (a reasonable analog of leaf area removed),
then

$$\omega = \Phi \chi \psi \times 10^{-4}$$

This assumption is contentious - remaining trees may take up the slack in transpiration when the canopy is partly removed. However, in the absence of evidence of this we must apply Occam's razor and use the simpler explanation. Should evidence come to light of a threshold cutting intensity below which the water table does not rise, any cutting below this level could be excluded from the calculation (see discussion later).
(4) If canopy removal causes salt release, the appearance of that salt in streams, and so eventually in the dam, will follow this pattern: there will be a lag between cutting and salt appearance (LAG), then

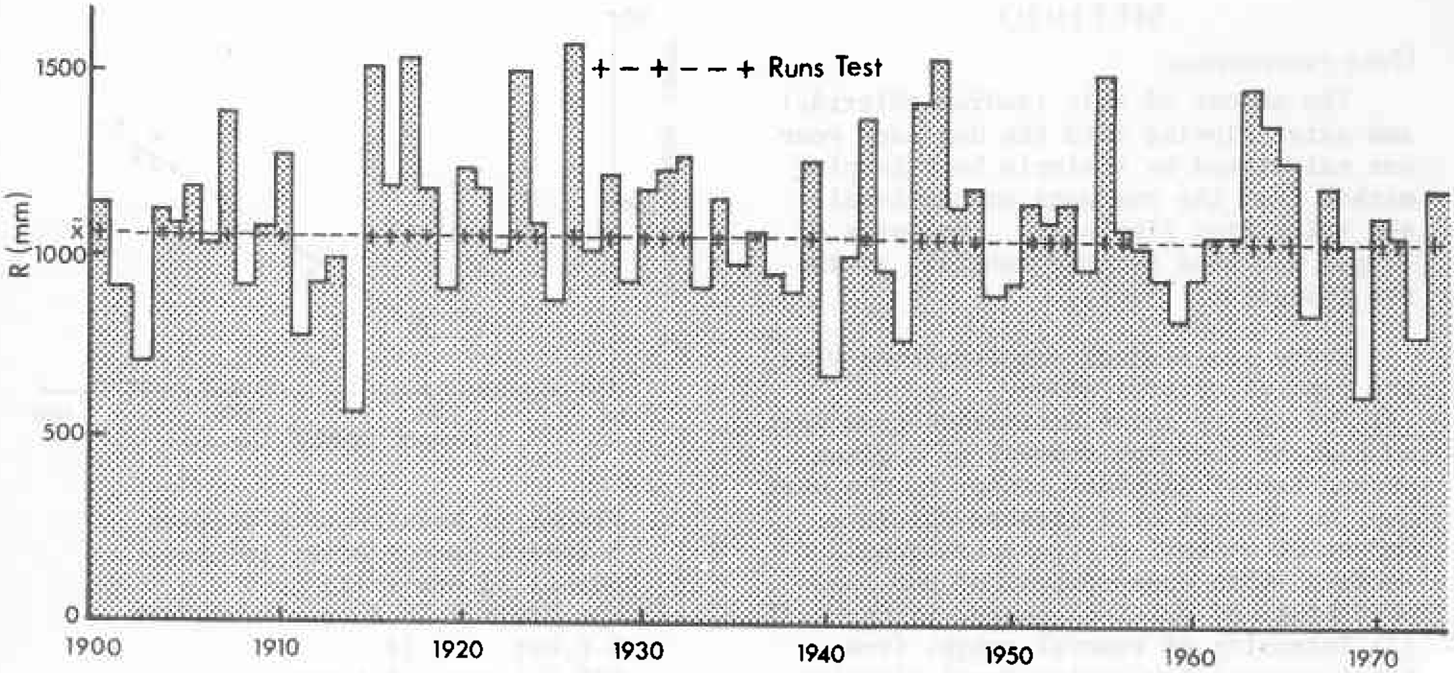

FIGURE 3a: Annual rain (R) plotted through time
Ho:random. r=37 α=0.05 Z=0.24. Accept Ho.

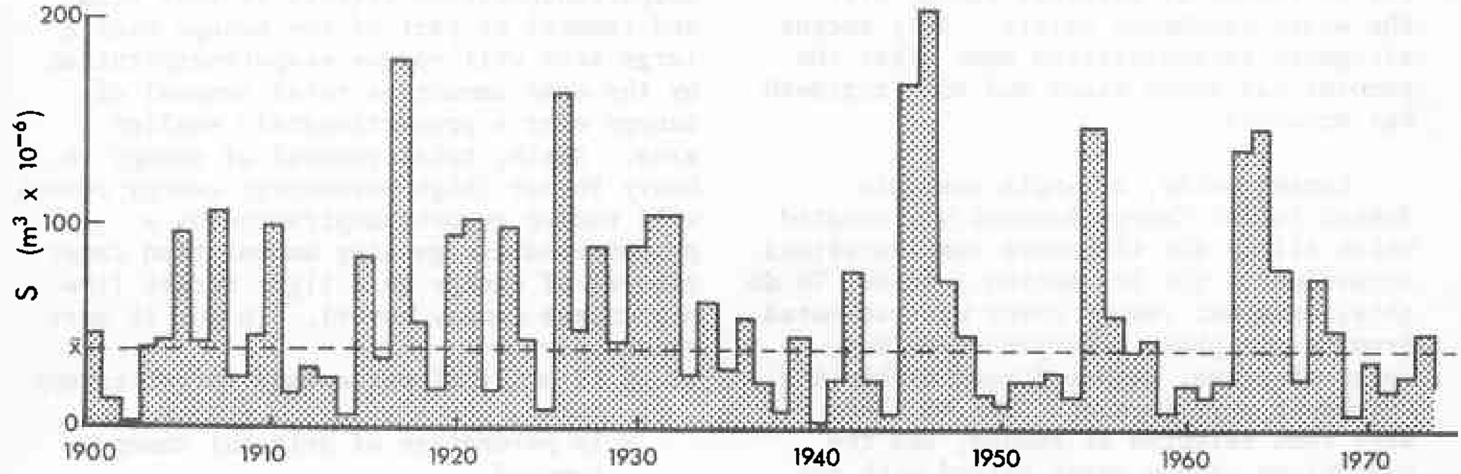

FIGURE 3b: Annual streamflow (S) plotted through time
Ho.random. r=35 α=0.05 Z=-0.24. Accept Ho.

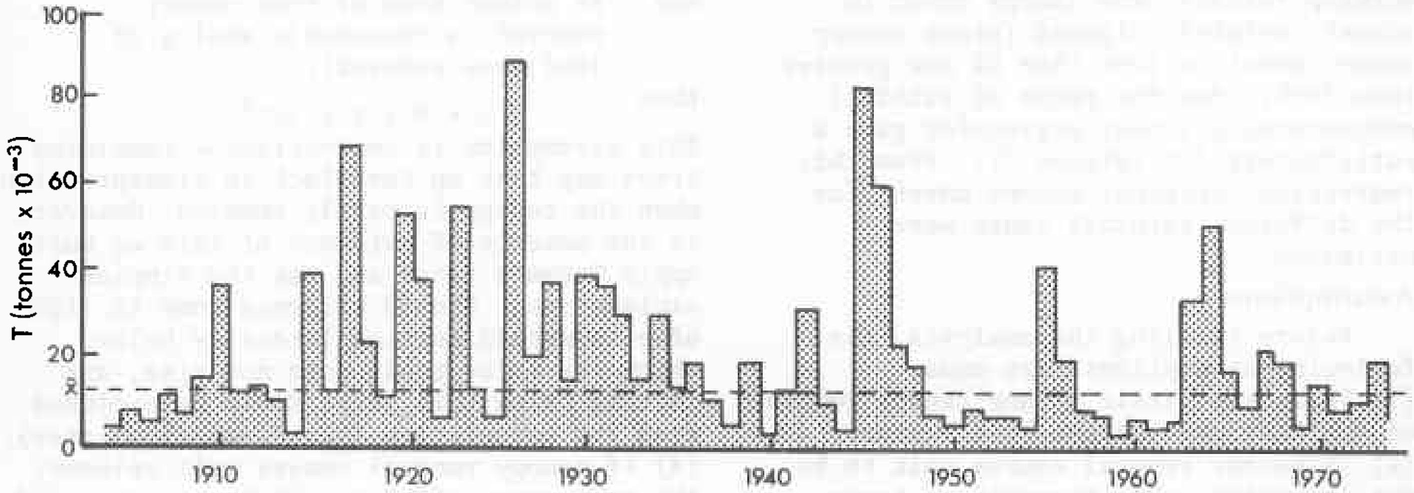

FIGURE 3c: Annual saltflow (T) plotted through time
Ho: random. r=28 α=0.05 Z=1.93. Reject Ho.

there will be a rise in salt flow up to a peak (BOOM), followed by a gradual decline in salt flow to its original level (BUST). LAG could range from a few days for areas of high rainfall close to the dam to many

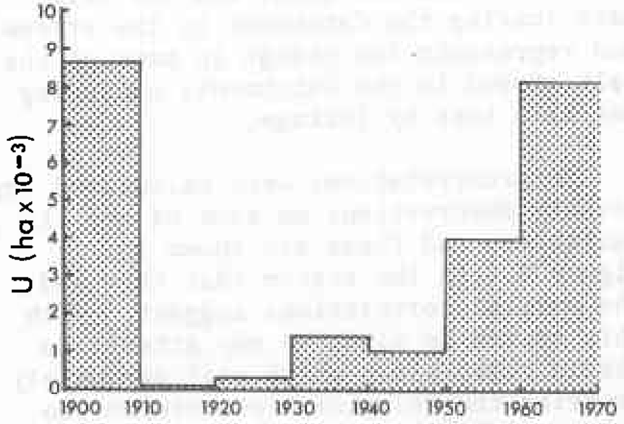

FIGURE 3d: Forest canopy removal (U) plotted through time

years for areas of low rainfall in the east of the Catchment. Similarly, one would expect the leaching period (BOOM and BUST) to be shorter in high than in low rainfall areas. Geomorphology may also affect the pattern.

(5) The water balance equation can be written as

$$W_t = W_{t-1} + R_t - F_t - E_t - L_t$$

where W_t is water in Catchment at end of t th time period

W_{t-1} is water in Catchment at end of (t-1) th time period

R_t is water input by rain in t th time period

F_t is water flowing out of Catchment in t th time period

E_t is evapotranspiration loss in t th time period

and L_t is water lost by leakage in t th time period

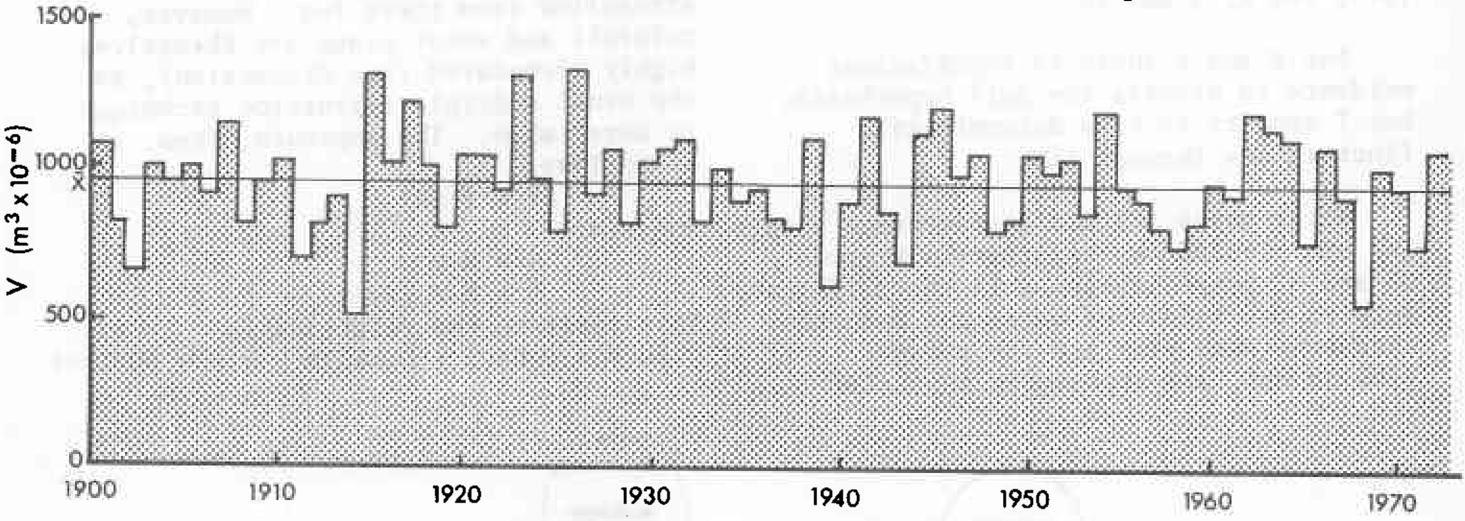

FIGURE 3e: Water usage (V) plotted through time

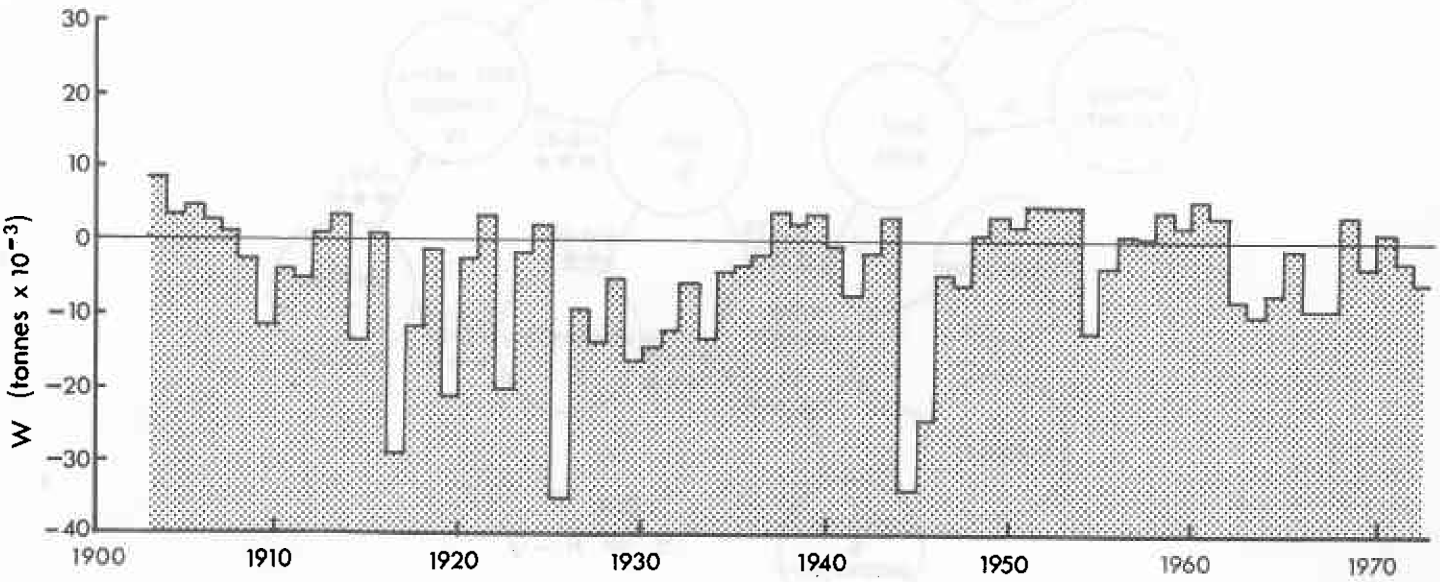

FIGURE 3f: Salt storage change (W) plotted through time

Since in this study the time unit is a year, the assumption is made that the volume of water in the Catchment on 1 January is approximately constant through time, i.e. that

$$W_t = W_{t-1}$$

Here we can say

$$E_t + L_t = R_t - F_t$$

Examination of variables

The four basic variables - annual rainfall (R), streamflow into dam (S), saltflow into dam (T) and forest canopy removal (U) - are plotted through time in Figure 3. No assumption of normal distribution was made for any variable, and the null hypothesis of random distribution through time was tested by the nonparametric Runs Test (Freund, 1971) for R, S and T.

For R and S there is insufficient evidence to dismiss the null hypothesis, but T appears to have deterministic fluctuations through time.

Water usage (V) and salt storage change (W) are plotted against time in Figures 3e and 3f respectively. V is the difference between the volume of water put into the Catchment each year and the amount flowing out, and represents the water stored in or lost from the Catchment by transpiration and leakage. W is the difference between salt mass entering the Catchment with the rain, and the salt mass leaving the Catchment in the streams, and represents the change in mass of the salt stored in the Catchment, excluding any salt lost by leakage.

Intercorrelations were calculated for seventy observations on each of the six variables, and these are shown in Figure 4 with the system that they and the partial correlations suggest. With this system in mind, we may attempt to obtain regressions which will adequately describe the relationships between the main variables. Since streamflow is determined by rainfall and water usage, it seems sensible to try to predict streamflow from these two. However, rainfall and water usage are themselves highly correlated (see discussion), so the usual multiple regression technique is unreliable. The approach, then, is as follows:

$$V = f\ (R)$$

and since

$$S = R - V$$

$$S = R - f\ (R)$$

This leads to the relationship

$$\ell n\ V = 0.8803 + 0.8657R \qquad r = 0.9925^{***} \quad n = 70$$

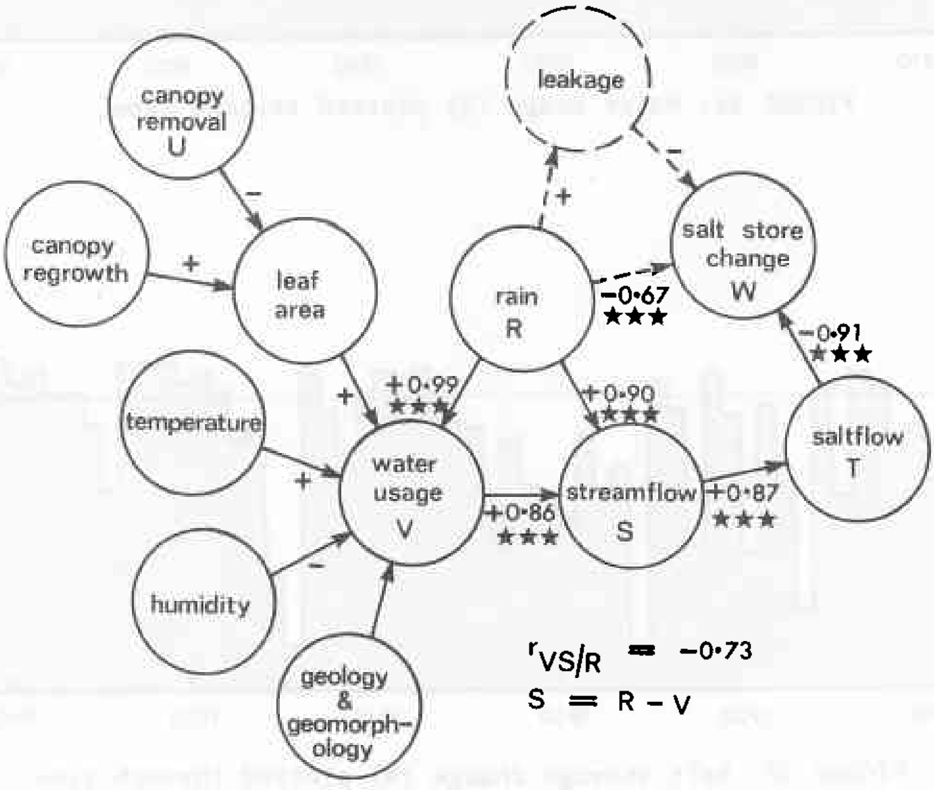

FIGURE 4: System chart

$\rightarrow V = 2.41\ R^{0.8657}$

$$\rightarrow S = R - 2.41\ R^{0.8657} \qquad (1)$$

In Figure 3b, streamflow appears to be randomly distributed through time. The departures of observed streamflow from that expected for a given rainfall are plotted through time in Figure 5; the hypothesis of random distribution can be confidently rejected for these residuals. For the period under study, streamflow seems to have a strong random component due to the strong random component of rainfall (rain may also have a deterministic component - see discussion). The random component of streamflow masks a deterministic component, probably caused by a deterministic element in the pattern of water usage through time.

Similarly, saltflow can be calculated as a function of streamflow

$$T = 193.71\ S + 4776 \qquad (2)$$

$r = 0.8699^{***}$
$n = 70$

The departures of observed saltflow from that expected from streamflow observations are plotted through time in Figure 6. Again we conclude that the residuals are not randomly distributed through time.

From Assumption 4, the hypothetical effect of canopy removal on salt release is shown in Figure 7. From Figure 6 we see that we need a "forgetting" function which will describe this rise and fall pattern. A general form could be

$$f(t) = \begin{cases} t^{\alpha} \exp(-\beta t) & \text{for } t > 0 \\ 0 & \text{elsewhere} \end{cases}$$

We can now introduce a Salt Release Index (call it Ω) which is the sum of the areas of canopy removed in preceding time units operated on by f(t) to allow for changing rate of salt release. Hence

$$\Omega = \sum_{t=1}^{j+k} U_{n-t}\ f(t)$$

where

- U_{n-t} is the area of canopy removed in the (n-t)th time unit
- i is time units of LAG
- j is time units of BOOM
- k is time units of BUST
- t* is time units since canopy removal
- and t is (t*-i)

From examination of the records of canopy removal and saltflow, a LAG of zero, a BOOM of two decades, and a BUST of three decades may explain the pattern of salt release which followed the ringbarking around the dam. The absence of LAG is reasonable when looking at time units of a decade since the ringbarking took place in

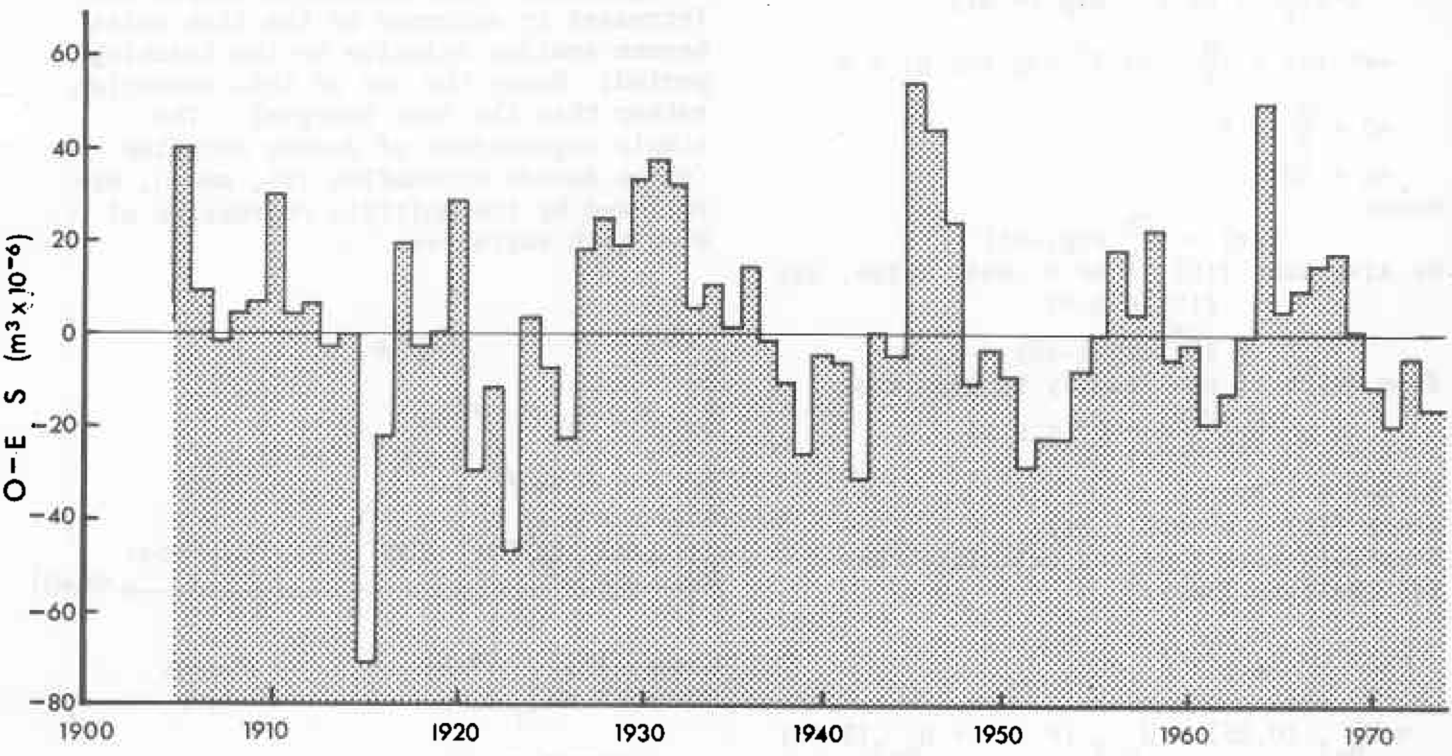

FIGURE 5: Streamflow residuals through time

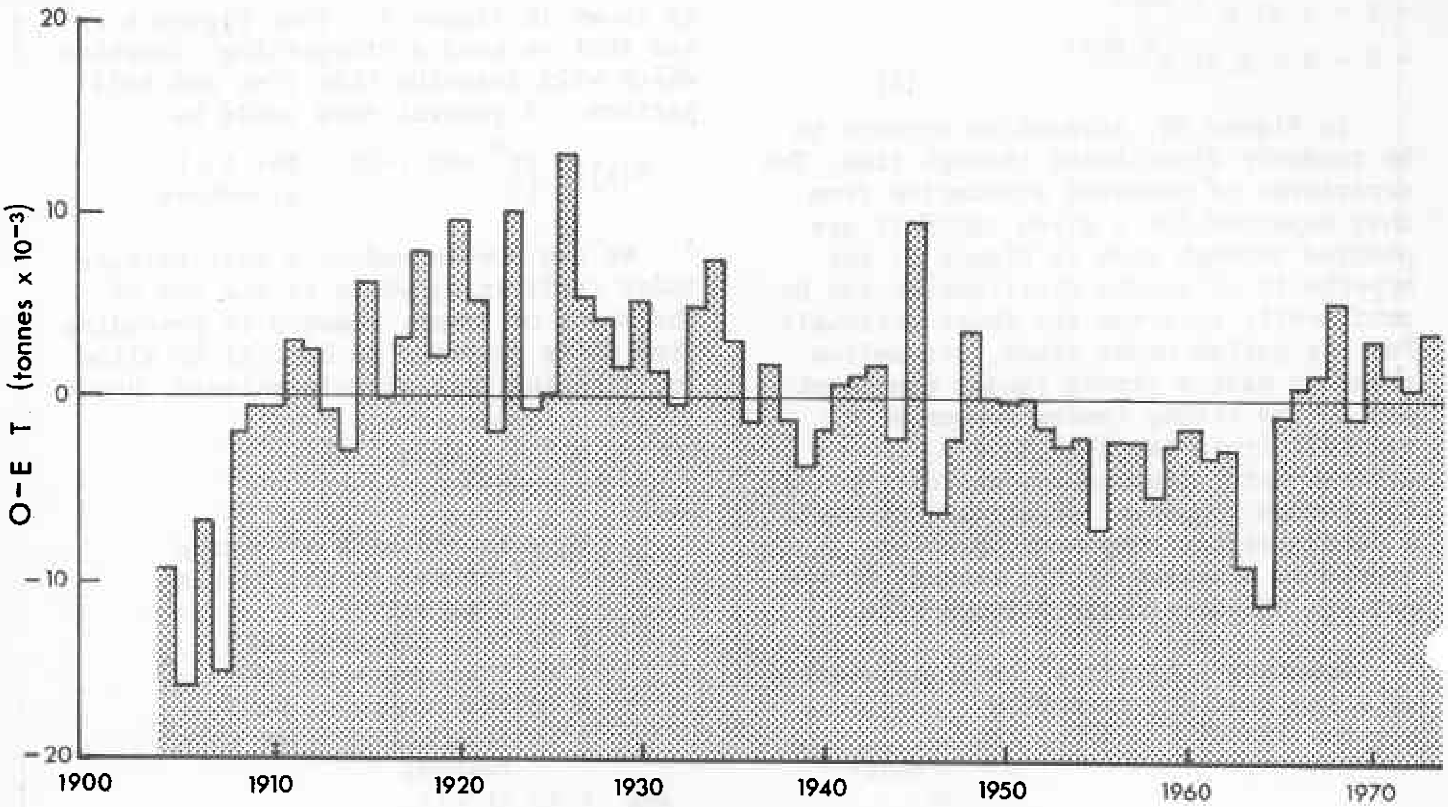

FIGURE 6: Saltflow residuals through time

a high rainfall zone close to the dam. The function for these periods is calibrated as follows. Let

LAG = 0
BOOM = 2
and BUST = 3.

Start with $f(t) = t^{\alpha} \exp(-\beta t)$. We want $f'(2) = 0$. Well,

$$f' = (\frac{\alpha}{t} - \beta)\, t^{\alpha} \exp(-\beta t)$$

$$\rightarrow f'(2) = (\frac{\alpha}{2} - \beta)\, 2^{\alpha} \exp(-2\beta) = 0$$

$$\rightarrow 0 = \frac{\alpha}{2} - \beta$$

$$\rightarrow \alpha = 2\beta$$

Hence

$$f(t) = t^{2\beta} \exp(-\beta t)$$

We also want f(5) to be a small value, say

$$f(5) \leqslant 0.01$$

$$\rightarrow 5^{2\beta} \exp(-5\beta) \leqslant 0.01$$

from which it can readily be seen that

$$\beta \geqslant \frac{\ell n\ 0.01}{2\ell n\ 5 - 5} \simeq 2.59.$$

So let $\beta = 3$.
Hence $f(t) = t^6 \exp(-3t)$.
From this result we can calculate the Salt Release Index:

$$\Omega_n = \sum_{t=1}^{5} U_{n-t} f(t)$$

$$\simeq U_{n-1}(0.05) + U_{n-2}(0.16) + U_{n-3}(0.09) + U_{n-4}(0.03) + U_{n-5}(0.01).$$

By substituting the appropriate U_{n-t} we obtain a value of Ω for each decade, and can compare this with other variables suitably summed over the same period. It will be seen that the weightings in the summation for Ω are the ordinates of the "forgetting" function, and represent rate of salt release. This gives a crude integration. This method is simple and increases in accuracy as the time units become smaller relative to the leaching period; hence the use of this summation rather than the true integral. The simple regressions of decade saltflow (Φ) on decade streamflow (Θ), and Ω, are followed by the multiple regression of Φ on both variables.

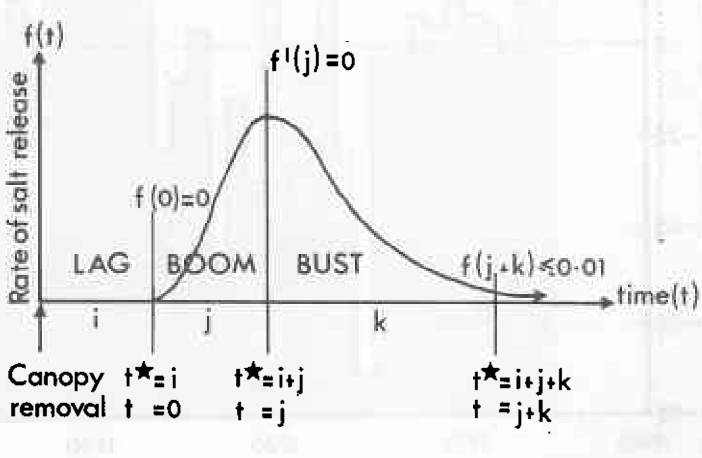

FIGURE 7: Diagram of assumed salt-release pattern

$\Phi = 437.659\Theta - 85269.592 \quad r = 0.8685^{*} \quad n = 7$

$\Phi = 91.139\Omega + 98767.492 \quad r = 0.8025^{*} \quad n = 7$

$\Phi = 305.59600\Theta + 50.741\Omega - 42657.945$

$R = 0.9408^{***} \quad n = 7$

Where $\Phi = \sum_{i=1}^{10} T_i$ (T_i in tonnes),

$\Theta = \sum_{i=1}^{10} S_i$ (S_i in $m^3 \times 10^{-6}$),

and $\Omega = \sum_{t-1}^{5} U_{n-t}\, t^6 \exp(-3t)$ (U_{n-t} in ha).

Test of Ho : $\rho = 0$

Test statistic $= \sqrt{\frac{n-3}{2}} \cdot \frac{(1+r)(1-\rho)}{(1-r)(1-\rho)}$

$= 3.4712$

Pr.($z \geq 3.47$ | Ho) $\leq 0.0005 \rightarrow$ reject Ho. In words, the probability of a correlation of 0.9408 for seven paired observations, if there were no correlation between the populations from which they are drawn, is less than 0.0005. (The population is assumed to be normal.)

RESULTS

Using the above multiple regression, saltflow was calculated from rainfall and canopy removal for the seven decades. These calculated values were then compared with the observed values, and both are given in Table 2.

TABLE 2

Observed and expected saltflow in tonnes

Decade	O	E
1	76 027	87 526
2	172 751	141 941
3	217 046	223 504
4	169 833	162 396
5	177 314	174 038
6	95 435	96 568
7	137 679	160 111

$R = 0.9408^{***}$

DISCUSSION

No great claims are made for the predictive accuracy of the model since the data on which it is based are few, and often only approximations. We see, however, that there is a high correlation between the saltflow observed and that calculated from the model. It may be argued that the model is calibrated on one major event: the ringbarking. This is so - but let us examine the fact more closely.

The ringbarking took place mainly in an area of high rainfall (1000-1200 mm) very close to the dam. Previous workers have found that such areas have the lowest salt store, there being up to five times more salt stored in the lower rainfall zones to the east (Dimmock et al., 1974). Also, one would, as discussed in Assumption 4, expect a high rainfall zone to have a shorter lag, and to start and finish leaching more rapidly than the eastern zone. Most of the recent (1950 onward) canopy removal has taken place in medium or low rainfall areas, at greater distances from the dam. Thus, calibrated on the ringbarking, the model would be expected to underestimate the lag, the leaching period, and the volume leached, for canopy removal in the low rainfall zone. The fact that the expected saltflow for the last two decades is greater than that observed is consistent with an underestimate of LAG. It remains to be seen whether the leaching period and the volume leached will be greater than that from the ringbarked area, and this should be a matter of concern to water-supply authorities.

The volume of rain falling on the Catchment is highly correlated with the volume of water apparently used by the Catchment. One probable reason for this is that the more rain there is, the more free water there is available for evaporation from the ground, and from leaf and stem surfaces. An alternative, or more likely an associated reason, may be that the more water available in the soil, the more the vegetation takes up and eventually transpires. This conflicts with Assumption 3 where it is supposed that if a tree is removed the water which it would have transpired remains untranspired. This is possibly incorrect - when a tree is removed other plants, including trees, in the vicinity may extend their root systems to exploit the available water. However, as the main tree species is jarrah which seems to obtain most of its water by deep sinker roots almost reaching the water table (Kimber, 1974), Assumption 3 is retained as the simplest explanation. Further work may require that it be modified.

Another flaw in this study is that it takes no account of the effect of geomorphology on salt leaching. Landform probably affects salt storage and salt leaching (Shea and Hatch, 1976), and probably a different LAG, BOOM and BUST should be used for each type of surface. For a more intensive study, a composite model with different parameters for different landforms (and rainfall zones) would be better.

For the period studied, rainfall seemed to behave in a random fashion. With the statistical test used, and the data available, no trend or cycle was found for Mundaring rainfall. Perhaps a more sophisticated time series technique, or a longer record, would reveal one or both.

The assumptions made about salt release are similar to assumptions one could make about water release after vegetation removal: the volume of streamflow follows a LAG, BOOM, BUST pattern with evapotranspiration decreasing after removal, then increasing with regrowth of vegetation. The LAG may be dependent on season of cutting. The coarseness of the cutting data precluded the use of the model for predicting water release after cutting, but should better data become available the model may be worth testing.

CONCLUSIONS

(1) There is almost certainly a causative link between removal of forest canopy and fluctuations in stream salinity within the Helena Catchment.
(2) This deterministic relationship is obscured by a strong random component, owing mainly to fluctuating annual rainfall.
(3) Once most of the noise is removed, the pattern of salt release can be successfully mimicked by modelling canopy removal records according to certain stated assumptions.
(4) No claim is made that these assumptions are true - only that they are the most reasonable in the writer's present state of knowledge.
(5) The data used in this study are few, and, especially for canopy removal, approximate. The model may be worth testing on a more accurate set of numbers.
(6) Using a composite of sub-models where each sub-model represents a different landform and rainfall zone, each with different LAG, BOOM, and BUST, would be a worthwhile refinement if such detailed data were available.

ACKNOWLEDGEMENTS

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