DEPARTMENT OF CONSERVATION AND ENVIRONMENT

LAND MANAGEMENT & WATER QUALITY

A Seminar on current Research into the effects of Land use on Stream Salinity and Turbidity in South Western Australia.

Friday 24th, September 1976.

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109 Broome St, Cottesloe.

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PROGRAMME AND MAIN SPEAKERS

8.45 - 9.00	Registration
9.00 - 9.10	Opening - Mr R. Perry, Division of Land Resources Management, CSIRO
9.10 - 9.40	Hydrologic and geomorphic background - A. Peck (CSIRO)
9.40 - 9.50	Discussion
9.50 -10.20	Effects of agriculture on stream quality - T. Stoneman (Dept of Agriculture)
10.20 -10.40	Discussion

Morning Tea*

11.00 -11.30	Effects of forest diseases and plantations - J. Havel (Forests Dept)
11.30 -12.00	Effects of bauxite mining - T. Bestow (Geological Survey)
12.00 -12.30	Discussion

Lunch*

1.45 - 2.15	Effects of the woodchip industry - D.B. Collett (Public Works Dept)
2.15 - 2.30	Discussion
2.30 - 3.00	Role of process modelling - R. Luxmoore (CSIRO)
3.00 - 3.10	Discussion

Afternoon Tea*

3.30 - 4.00	Research into land-use planning - A case study - F. Batini (Forests Dept)
4.00 - 4.15	Discussion
4.15 - 4.55	Summary - Professor W. Stern, Institute of Agriculture, University of Western Australia
4.55 - 5.00	Conclusion

Chairman : Dr M.J. Mulcahy
Department of Conservation and Environment

* Light Refreshments Provided

CONTENTS

INTRODUCTION

There has long been an awareness of the dangers of soil salinity following clearing of vegetation for agricultural development in south western Australia, and the Department of Agriculture has been monitoring its extent over a number of years. Clearing also affects the quality of water yielded from catchments in which it takes place.

The programmes outlined in the papers to be presented here are essentially aimed at providing the technical basis for predicting such effects in a quantitative way, whether the clearing is for agriculture, where annual plants replace the perennial forest trees, or for bauxite mining, where soil conditions are drastically changed in addition to removal of the forest, or by forest operations themselves, which in general replace mature forest by younger communities.

The results coming forward indicate that such a basis will be forthcoming, and open up the possibility of reconsidering policies with respect to water supply catchment management.

Department of Conservation & Environment,
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M.J. Mulcahy
CHAIRMAN.

HYDROLOGIC AND GEOMORPHIC BACKGROUND TO PROBLEMS OF LAND MANAGEMENT AND WATER QUALITY IN THE DARLING RANGE

A.J. Peck and E. Bettenay

CSIRO Division of Land Resources Management
Perth.

Abstract

Salinity and turbidity are terms used in the consideration of water quality. In south-western Australia, increasing stream salinity has been identified as a major water pollution problem. Solutes are discharged into streams by water moving through salt-laden soils and weathered rock. Water transport through porous media may be simulated, but characterization of the material is expensive, and very large computers may be needed. Simulation of solute transport is generally more difficult and less accurate. Modelling of groundwater systems can provide useful insights into their role in the salinity problem. The slow response of groundwater systems in the Darling Range is emphasized.

INTRODUCTION

Many physical, chemical and biological characteristics of a water source must be considered in an assessment of its suitability for any specific purpose. In some cases man's activities have significantly changed these water quality characteristics from their pristine conditions, and the water source is said to be polluted. For example, European man's disturbance of natural forest ecosystems in south-western Australia often leads to an increase in concentration of soluble salts in the streams which drain this area. The Senate enquiry into water pollution concluded that this is a major problem in W.A., and they recommended that further research should be undertaken (Anon., 1970).

The magnitude of the stream salinity problem in this region is revealed in records of streamflow and salinity (Anon., 1972). However, the situation is not static as demands grow for both water and multiple use of catchment areas.

Although the major water quality problem in the region is undoubtedly the concentration of dissolved salts, there is also some concern about the turbidity of stream water. This paper briefly reviews physical processes affecting stream salinity and turbidity, and hypotheses associated with the salinity problem. Other papers in the seminar will describe the results of current research programs aimed at maintaining or improving yields of good quality water from multiple use catchment areas. More specifically, the objectives of the research are to:

(i) Delineate areas where disturbances of forest ecosystems would bring about unacceptable increases of stream salinity; and

(ii) Develop land use strategies, if possible, to maintain or improve the quality of stream water while the land yields other desirable products.

Since the terms salinity and turbidity are frequently used rather loosely, we consider the terminology briefly before proceeding to a discussion of physical processes and hypotheses.

SALINITY AND TURBIDITY

In its most common and recommended usage the term salinity refers to the total soluble salt (TSS) concentration in a water sample. TSS is calculated from a measurement of the electrical conductivity of the water using a relationship which has been determined empirically for waters with the same, or at least similar ionic composition. Criteria for water for domestic supply or irrigation usage do not include TSS explicitly. For domestic purposes, the concentration of specific ions is preferred, and for irrigation the criteria are usually expressed in the basic measurement of electrical conductivity (Hart, 1974). We favour the reporting of electrical conductivity rather than derived values of TSS. Where TSS values are reported, the relationship used in their calculation should be reported too.

Another value which is sometimes referred to as salinity is the concentration of chloride ion expressed as NaCl regardless of the proportion of Na^+ to other cations in the solution. We favour the presentation of results as Cl^- concentration since this is the factor actually measured, and assessment of a water supply for domestic use requires a knowledge of this quantity.

On some occasions the total dissolved solids (TDS) concentration is referred to as salinity. TDS is determined by weighing the residue after a water sample has been passed through a fine filter, and then evaporated to dryness. This residue may contain very finely divided particulate matter and other substances which have little effect on the electrical conductivity of the filtrate. Very few water samples are subjected to this treatment; when they are the results should be expressed as a TDS concentration, and the term salinity should not be applied.

In south-western Australia salinity (TSS concentration) provides an estimate of both Na^+ and Cl^- concentrations in stream waters since these are the dominant ions in the great majority of samples (Hingston, unpublished data).

Finely divided particulate matter in water attenuates and scatters light, and the water is said to be turbid. The turbidity of a water sample may be measured with an optical instrument which yields a result expressed in empirical turbidity units. This is a relatively simple measurement, and criteria for domestic water quality include turbidity measured in these units.

Since the scattering and attenuation of light in water depends on the size and shape of suspended particles, there is not a unique relationship between an optical measurement of turbidity and the concentration of particulate matter. However, the measurement of concentration by filtration of a water sample is sometimes preferred, and the data may be loosely and incorrectly referred to as measurements of turbidity.

WATER TRANSPORT IN POROUS MEDIA

The study and literature of fluid flow in porous media is spread across many branches of science and technology. A detailed review is not intended here. The reader should consult Scheidegger (1957) and Philip (1970) for more detail and references to other work.

Water movement in porous media such as soils and porous rocks is an example of viscous flow, and the Navier-Stokes equation of fluid mechanics applies. In media with very large voids (some limestones, volcanics and fissured rocks) turbulent flow conditions can develop, but normally the velocity of water movement is so small that the inertia terms in the basic equation can be neglected. However the geometry of the flow space (the voids in the medium) is so complex that this fundamental approach is impractical for natural porous materials.

A linear, empirical relationship between the rate of flow and the gradient of hydraulic potential (pressure plus elevation head) has been found to apply, except on occasions, in media with very large voids. This relationship is known as Darcy's law. By combination of the law of conservation of mass and Darcy's law, an equation can be derived to represent non-steady flow of water in a porous medium. Then simulation of water transport requires:

(i) Physical characterization of transport properties of the medium;

(ii) Specification of initial and boundary conditions appropriate for the situation to be simulated; and

(iii) Solution of the flow equation.

Examples of simulations may be found in the literature of soil physics (Philip, 1970) and groundwater hydrology (Polubarinova-Kochina, 1962). Powerful numerical methods have been developed for solution of the flow equation (Remson, Hornberger and Molz, 1970).

The problems in simulating water movement in soils and rocks are now the cost of adequately characterizing the medium, and the capacity of computers, rather than the physical understanding of the transport process. A major problem is the spatial variability of parameters describing the transport properties of natural soils and rocks. Usually some degree of uniformity is assumed, and reduced accuracy of simulation is tolerated.

SOLUTE TRANSPORT IN POROUS MEDIA

For a detailed review of solute transport in porous media the reader is referred to Fried and Combarnous (1971).

Solutes move within porous materials by convection and diffusion. An essential feature of the convective transport is the microscopic distribution of solution velocity. The range of velocities in an individual pore brings about a dispersion of solute, but this is modified by molecular diffusion between streamlines of higher and lower velocity. This interaction between convection and diffusion is a significant factor affecting solute dispersion in some situations.

In some porous media there is a macroscopis as well as microscopic structure. Examples are some fractured sedimentary rocks, quartz veins in rock which has weathered *in situ*, well aggregated soils, and soils containing old root channels or worm holes. This structure contributes to a macroscopic distribution of solution velocities. On this larger scale molecular diffusion between regions of higher and lower solution velocity is less effective than it is in more simple porous materials.

Exchange reactions between materials in solution and the particle surfaces of a porous medium, or transport between active and inactive pore space further influence solute transport. In most cases these processes retard solute movement relative to solution flow. An exception occurs when electrical charges on particle surfaces cause an enhancement of concentration of a particular ion in a region of relatively high solution velocity. This ion is then transported at a rate greater than the average solution velocity.

A basic requisite for simulation of solute transport in a porous medium is a satisfactory description of the distribution of solution velocities. Furthermore, the exchange properties of the medium must be suitably characterized. While there is a reasonable understanding of the physics of solute transport, the complexities of the processes in porous media are such that no great accuracy can be expected from attempts at quantitative prediction, particularly in field situations.

EROSION AND DEPOSITION OF SEDIMENT

The essential energy sources which bring about suspension of particulate matter in water are the kinetic energy of raindrops and moving solids, and the viscous drag of water moving over the soil surface. Physical and chemical factors within the soil can enhance or reduce erosion. For example plant roots and certain cementing agents maintain soil particles in larger and less readily movable aggregates, but factors such as adsorbed sodium which tend to reduce the capacity of soil to absorb water enhance runoff and erosion.

Even in stationary water finely divided particulate material can remain suspended indefinitely due to interactions of electrical charges on the particles. However, changes in ionic composition or concentration in the water can bring about deposition of the solids. High salinity (TSS concentration) flocculates suspended material which then tends to settle. Thus saline water tends to be less turbid than water of lower salinity.

The distribution of velocity in moving water tends to disperse finely divided particulate material which may be deposited in a region where for some reason the velocity decreases.

HYDROLOGY AND GEOMORPHOLOGY OF THE DARLING RANGE

The Darling Range is an ill-defined region in south-western Australia. For our purposes we take it to be bounded by the Darling Scarp to the west, and the 700 mm rainfall isohyet to the east. The northern and southern limits of the region of immediate interest are the Swan-Avon river and the Southern Ocean respectively.

Average rainfall in the Darling Range varies between 700 and 1500 mm/yr of which about 80% falls in the months May to October. Peak rainfall intensities occur during summer and autumn storms, but the rate of 25 mm/hr is only moderate. Maximum daily rainfalls occur in winter, and range up to 150 mm (Anon., 1965).

The geomorphology of the Darling Range has been described by Mulcahy *et al.* (1972) and Bettenay and Mulcahy (1972). Close to the Scarp, and in major valleys the basement rock is frequently exposed and soils are shallow. Consequently there tends to be appreciable runoff of rainfall, but little base flow. Where streams are cut deeply into the clays of the pallid zone the intersection of a permanent water table provides base flow, but there is rarely any direct runoff from the sandy gravels which form the surface layer of the deep lateritic profile. Further to the east valleys are more mature and streams are ephemeral. They flow in late winter and spring when the more permeable soil above the pallid zone clay becomes saturated with water. This shallow perched water system also appears to contribute appreciably to streamflow from the lateritic soils of the intermediate region.

Because rainfall in the Darling Range reaches its maximum in winter when evaporation is at its minimum, and the situation is reversed in summer, the seasonal variation in streamflow is large. A brief inspection of monthly flow data suggests that the seasonal variation in any one year is typically much larger than the variation of flow from year to year for any chosen month.

The combination of rainfall, soil depth and valley type results in a range of catchment efficiency for runoff generation. At the best, however, streamflow in this region amounts to only a moderate (25%) proportion of incident rainfall. In the eastern fringe of the region the runoff yield is rarely as much as 5% of yearly rainfall.

The relative importance of the higher rainfall areas in the Darling Range to the water resources of the south-west is better illustrated by comparing water yield from unit catchment area in absolute terms. Those areas receiving more than 1250 mm/yr in rainfall yield about 300 mm/yr or more in streamflow, but the yield drops to less than 35 mm/yr with rainfall of less than 750 mm/yr (Anon., 1972). Thus

1 ha of catchment in the higher rainfall regions typically yields as much streamflow as nearly 10 ha in the eastern Darling Range.

HYPOTHESES ON EFFECTS OF FOREST REMOVAL

More than 50 years ago Wood (1924) hypothesized that:

> "the killing of large timber on the hillsides, followed by decay of the roots, permits more water to enter (the subsoil - decomposed rock) than formerly. Moreover, if the surface is cultivated, the soil acts as a sponge to hold more water, which in turn drains into the underground channel (subsoil aquifer). It can be assumed then that more water will drain into (the subsoil aquifer) than can percolate away to the coast without raising the water-table. As a consequence of this, water will, if increased greatly, rise to the semi-impervious layer (overlying the subsoil aquifer), and if that has also been rendered pervious by decayed root holes near the water-course, the underground water will rise through it, and perhaps to the surface, bringing its salts with it."

While this hypothesis has been accepted in general terms by many people, Conacher and Murray (1973) suggest that lateral movements of water over the soil surface and in the more permeable surface soil may make a greater contribution to the redistribution of salt after clearing than does the deeper aquifer system.

The different water usage between native vegetation and exotic plants in the same soil and climate is generally believed to result from differences in growing season and rooting depth. Many species in the native vegetation are evergreen perennials whereas the common crop and pasture plants are annuals which grow in winter. Thus there is a contrast in the summer months (roughly November to April) between transpiring native plants and non-transpiring crop or pasture residues. Moreover, roots of the native plants are found to depths of 20 m whereas the common crops and pastures exploit water from depths of only 1 or 2 m of soil.

There are several other factors which affect plant water use in a given climate and soil. These include the capacity of the canopy to intercept and store rainfall, canopy albedo (which affects the reflection of solar energy), aerodynamic roughness of the canopy, leaf area and stomatal resistance, root density and distribution, and internal resistance to movement of water from the plant's roots to its leaves. It is unknown to what extent these may be important. Physical models of the evapotranspiration process can aid in understanding the relative importance of these different factors (see the paper by Dr. R.J. Luxmoore for this seminar).

For hydrologic purposes the lateritic soil profile which is found through much of the Darling Range area may be characterized by a shallow layer of high permeability (sandy loam; gravelly sand; bauxite) overlying a much deeper layer of much lower hydraulic conductivity (the sandy-clay pallid zone). These materials have been sampled on many occasions and their properties are reasonably well documented. The bottom of the profile is defined by material which is very much harder than the overlying clay, and is generally believed to be basement rock. However, the basement has been found to be fractured in some areas, and it has been suggested that the uppermost layers of rock may be highly permeable (O'Driscoll, personal communication). The existence of such a semi-confined aquifer is consistent with some observations on a groundwater system in the Darling Range (Peck, unpublished data).

SOME REMARKS ON DYNAMICS OF GROUNDWATER SYSTEMS

These remarks are intended to illustrate the contribution that very simple quantitative modelling can make to the understanding of groundwater systems associated with salinity problems. Dr. Luxmoore will broaden discussion of the role of physical modelling in his paper for this seminar.

The "deeper aquifer" hypothesis is considered since this has been the essential feature in the salinity problems which the authors have studied in detail (Bettenay *et al.*, 1964; Peck, unpublished data).

Reduced evapotranspiration in an area from which native vegetation has been removed will tend to raise the local water table. The maximum rate at which the water table will respond to local input alone may be estimated from the ratio of the net rate of recharge to groundwater (R) and the quantity of water required to bring about unit change of depth of the water table (S). Peck and Hurle (1973) estimated R to lie in the range 0.023 to 0.065 m/yr for most catchments in the Darling Range. (These values are consistent with the different water usage of forest and grassland measured in South Australia.) Bestow (unpublished data) has estimated S to be 0.039 for the pallid zone clays in the Darling Range. Thus water tables could be expected to rise at rates of up to 0.6 or 1.6 m/yr. These figures may be compared with data from two bores near Bakers Hill where the average rates are 0.25 and 0.44 m/yr respectively (Williamson *et al.*, unpublished work). When the water table is originally at a depth of 15 or 20 m, there will obviously be a lag of several years before it contributes to a surface salinity problem, or discharges water by seepage.

Native vegetation may be removed from only restricted areas (for example, bauxite mining pits), or the difference in evapotranspiration between native and exotic plants may be non-uniform due to the spatial distribution of soil properties. In either case groundwater mounds will develop beneath areas where the net recharge to groundwater is relatively large. Water then moves laterally from these mounds to discharge sites such as certain streams and seepage areas. Polubarinova-Kochina (1962) has analysed the groundwater response to localized recharge. She shows that the characteristic time scale is SL^2/hK where S has been defined above, L is the half-width of a recharge strip, h is the depth of the water-saturated aquifer material, and K is its hydraulic conductivity. Taking s = 0.039 as before, L = 100 m for a bauxite mining pit, h = 10 m and K = 0.01 m/d for the

Darling Range (Yendle *et al.*, unpublished data) we find the characteristic time to be of order 10 years. A significantly greater time must elapse before there would be any change in the discharge to a stream several pit widths downslope. On the other hand, the hypothesized fractured rock aquifer may reduce the characteristic time to order 1 year.

Polubarinova-Kochina (1962) also examines the decay of a groundwater mound after recharge ceases. This decay takes place by flow outwards from the mound. She shows that at a downslope distance equal to the width of a strip recharge area the water table height is substantially affected (about 15% of the original change beneath the middle of the strip) after a time 40 times greater than the characteristic time. Using the parameters introduced above, therefore, disturbance to the groundwater system may be appreciable even after a time of order 40 to 400 years depending on the existence or absence of a fractured rock aquifer.

These analyses of the spreading and decay of a groundwater mound consider a system which is a considerable simplification of that associated with the removal of native vegetation in the Darling Range. Moreover we are uncertain of the magnitude of some of the parameters of aquifers in this region. Consequently the numerical results should be considered with caution. However, it is reasonable to conclude that groundwater responses will be very slow, and that the modelling approach can provide valuable insights into rates of change.

Peck and Hurle (1973) showed that there is a large net loss of Cl^- from partly cleared catchment areas in the Darling Range. This was interpreted to result from increased discharge of saline groundwater due to reduced evapotranspiration after farming. They estimated the present rate of discharge of groundwater G, and the storage of groundwater W. The ratio of these terms, W/G is known as the conventional residence time for a groundwater system. It can also be taken as a characteristic time for leaching of a simple ion such as Cl^- from the system. Using data from the Darling Range, Peck and Hurle calculated characteristic times for Cl^- leaching of order 10 to 100 years for the higher and lower rainfall zones respectively. These calculations use good data, but they depend on several simplifying assumptions so they should be regarded only as order-of- magnitude estimates. They suggest that a substantial improvement in stream Cl^- concentrations should be observed within about 10 years of clearing in high rainfall areas. But salinity is a very minor problem in these areas, and the changes may be hard to detect. In the lower rainfall region of the Darling Range, substantial improvement of stream Cl^- concentration should not be expected within 100 years of clearing unless satisfactory methods of restoring the pristine hydrologic regime are implemented.

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EFFECTS OF AGRICULTURE ON STREAM QUALITY

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INTRODUCTION

The primary purpose of this paper is to describe the nature of recent and current research projects concerned with the effects of agricultural development on stream quality and to report results obtained to date from these projects. Remarks on water quality are confined to salt content, turbidity aspects being discussed in a later paper in the Seminar.

HISTORICAL

Salinisation of soils and water supplies due to human activities has been evident for thousands of years, one of the earliest examples being the Valley of the Euphrates where ancient civilizations prospered from irrigation, but eventually suffered from salt accumulation due to the development of shallow water-tables (Jacobsen and Adams, 1958). The major salinity problems of the world since those early irrigation schemes have continued to be associated with irrigation.

However, development for agriculture under dryland farming conditions has also led to an increase in soil and stream salinity; e.g. Canada (Greenlee *et al.*, 1968), U.S.A. (Sandoval *et al.*, 1964), and Australia, particularly Western Australia (Malcolm and Stoneman, 1976).

In the south-west of Western Australia it is recognised that the salt contents of many rivers and streams have increased due to removal from the catchments of the original native vegetation for development for agriculture. The salinity problems arise, as in the case of irrigation, because of changed hydrological conditions, but the processes involved are much more subtle than the obvious changes in water inputs in irrigated agriculture.

Clearing for agriculture results in the development of salinity problems in varying degrees in all parts of the agricultural areas but these remarks are confined to the higher rainfall portion of the State with an average annual rainfall of greater than about 500 mm; this being the only area with any potential for storage of large volumes of surface water for community use.

Wood (1924) was the first to suggest that removing the native vegetation leads to increased stream salinity, and Weller (1926) produced data to show that under native forest on a Mundaring catchment there was an approximate balance between inputs and outflows of salt. Burvill (1947) drew attention to the store of soluble salts in the deeper subsoils of the W.A. agricultural areas and to the data which Teakle and Burvill (1938) had obtained, indicating that clearing resulted in leaching of soluble salts down the soil profile.

From 1952 to 1956 a small scale stream sampling programme for selected streams in the Collie catchment was conducted (Anon., 1956) which demonstrated a relationship between stream salinity and catchment clearing. In a later study (Anon., 1958) it was reported that the salinity of the major branches of the Collie River was related to the incidence of clearing in the catchments. As a result of the concern for the future quality of Wellington Dam water, the Advisory Committee on Water Purity recommended that alienation of land on the Collie catchment should cease. That recommendation was accepted.

A mathematical study by Gwynne (1972) determined that the salinity of water in Wellington Dam between the years 1940 and 1968 had increased at the rate of a little over 4 mg/l NaCl per year and he predicted that, if the trend continued, irrigation water would become sufficiently saline to limit production of irrigated pasture. Loh (priv. comm.), using a more sophisticated analysis of records, has shown that the rate of increase of salinity of Wellington Dam water in the period 1968-74 had increased to 15 mg/l NaCl per year.

Peck and Hurle (1973) studied the chloride balance for fifteen farmed and forested catchments in the south-west of the State. Their results showed that saltflow from forested catchments is only slightly greater than the total saltfall from rain and dust. However, saltflow from the catchments with appreciable areas of agricultural clearing is much larger than saltfall by up to 690 kg chloride/ha/year, or a factor of 21 (see Table 1). Peck and Hurle calculated that characteristic times for equilibration of chloride input and output on farmed catchments would range from 30 to 400 years.

Peck (1975) has also collated long term records for the Blackwood River which show the appreciable increases in stream salinity recorded between about 1910 and 1970 (Fig. 1).

RECENT AND CURRENT RESEARCH PROJECTS

Since 1969 there has been a considerable upsurge in the amount of research being undertaken in relation to the effects of changed land use on water quality in the south-west of Western Australia. The studies fall into three main groups, each group owing its origin to the type of land use change involved. The categories of changes are:

(i) Forest to agriculture

(ii) Wood chipping of native forest

(iii) Bauxite mining in forested areas.

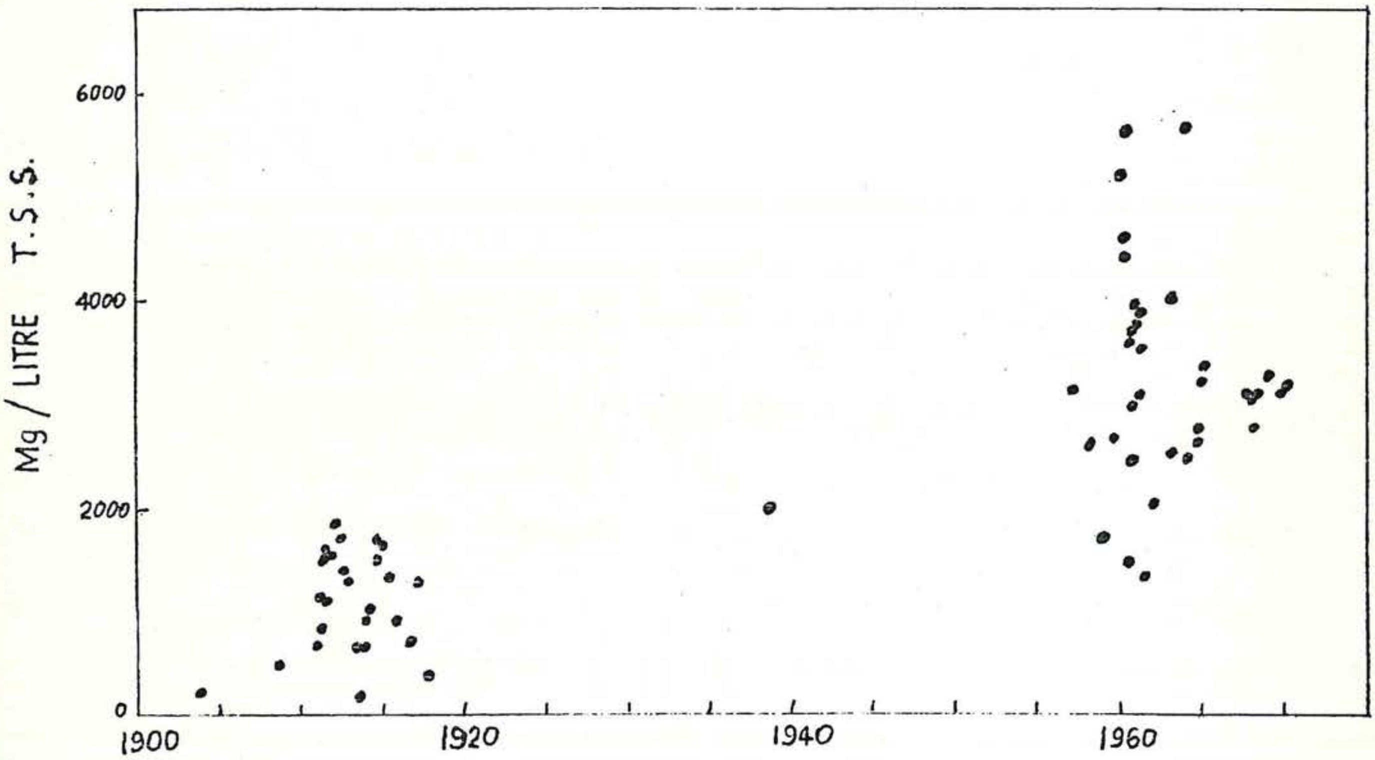
TABLE 1

SALT (CHLORIDE) BALANCES OF THE CATCHMENTS STUDIED

(Peck and Hurle, 1973)

Catchment	Salt Fall kg/ha yr	Salt Flow kg/ha yr	Salt Flow less Salt Fall kg/ha yr	Salt Flow/ Salt Fall
Predominantly Forested Catchments:				
Julimar	53	78	25	1.5
Seldom Seen	118	163	45	1.4
More Seldom Seen	116	137	21	1.2
Waterfall Gully	109	178	69	1.6
North Dandalup	133	175	42	1.3
Davies	126	135	9	1.1
Yarragil	97	130	33	1.3
Harris	84	131	47	1.6
Catchments with substantial areas of cleared farmland:				
Brockman	80	342	260	4.3
Woorooloo	78	420	340	5.4
Dale	24	460	440	19
Hotham	48	369	320	7.7
Williams	31	650	620	21
Collie East	50	740	690	15
Brunswick	111	346	240	3.1

FIGURE I TRENDS IN SALINITY - BLACKWOOD RIVER AT BRIDGETOWN (PECK 1975)



(i) Development for agriculture.

At the CSIRO Yalanbee Research Station at Bakers Hill (mean annual rainfall 600 mm), catchment studies began in 1969 on two small catchments (17 and 19 ha) with the aim of monitoring all aspects of the salt and water balance for a period before, during and after clearing of one of the pair of catchments. One of the catchments was cleared in December 1973, having had 5 years for calibration. The available data on runoff from these catchments are presented in Table 2.

Changes in groundwater levels and salinities are being monitored by means of 36 deep test wells and two shallow holes. The test wells are also used to measure hydraulic conductivity using a rate of recovery technique. Values for hydraulic conductivity range between 0.001 and 0.01 m/day (Peck *et al.*, 1973).

Data collection commenced in 1974 under a joint Public Works Department/CSIRO project concerned with catchments within the Wellington Dam catchment area (Fig. 2). The objective is to study the effects of clearing of native forests for agriculture and the subsequent effects of this development on stream water quality. Two catchments were selected in a high rainfall area with shallow soil and appreciable relief, and three in poorer drained drier conditions where salinity problems are anticipated. The two high rainfall catchments (Salmon and Wights) are in the Salmon Brook area immediately south of Wellington Dam and the three lower rainfall catchments (Ernie, Lemon and Dons) are in the Bingham River catchment about 30 kilometres east of Collie.

Some tabulated information about these catchments is presented in Table 3.

All catchments are still in the virgin state with measurements being collected of all components of the salt and water balance for the third successive year under forest conditions. At the end of 1976 it is planned to clear and develop for agriculture one of the two high rainfall catchments and two of the three low rainfall catchments.

Runoff and saltflow data for two of the Collie catchments are shown in Table 4.

Results obtained to date for hydraulic conductivities of the pallid zone from Wight's catchment (in the high rainfall part of the Collie River catchment) are particularly interesting (Hurle and Yendle, priv. comm.). Although the range in values is large, 0.0007 m/day - 0.18 m/day, the geometric mean and median values are both 0.005 m/day. Ninety per cent of values were greater than 0.001 m/day and 33 per cent greater than 0.01 m/day (Fig. 3).

Harley (priv. comm.) has reported values for hydraulic conductivity of 0.035 m/day for the pallid zone at Del Park (near Jarrahdale). Thus apart from the long term purpose of the various experimental catchment studies in progress, much useful data is starting to accumulate and is of particular importance as inputs for modelling studies.

TABLE 2

CSIRO CATCHMENTS - "YALANBEE", BAKERS HILL

Year	Site	Rainfall mm	Run-off mm	% Run-off of Rainfall
1969†	E	22	0	0
	W	22	0	0
1970	E	525	2.7	0.5
	W	535	0.2	0.03
1971	E	583	1.7	0.3
	W	596	0	0
1972	E	374	2.8	0.7
	W	389	0	0
1973	E	650	26.9	4.1
	W	677	1.3	0.2
1974	E	732	45.0	6.1
	W	745	45.3	6.1
1975*	E	353	Not available	-
	W	355	39.1	11.1

† Measurements began September 17, 1969.

* Applies for year up to September 8, 1975.

Note: E is Eastern Catchment - control

W is Western Catchment - cleared for agriculture in December, 1973.

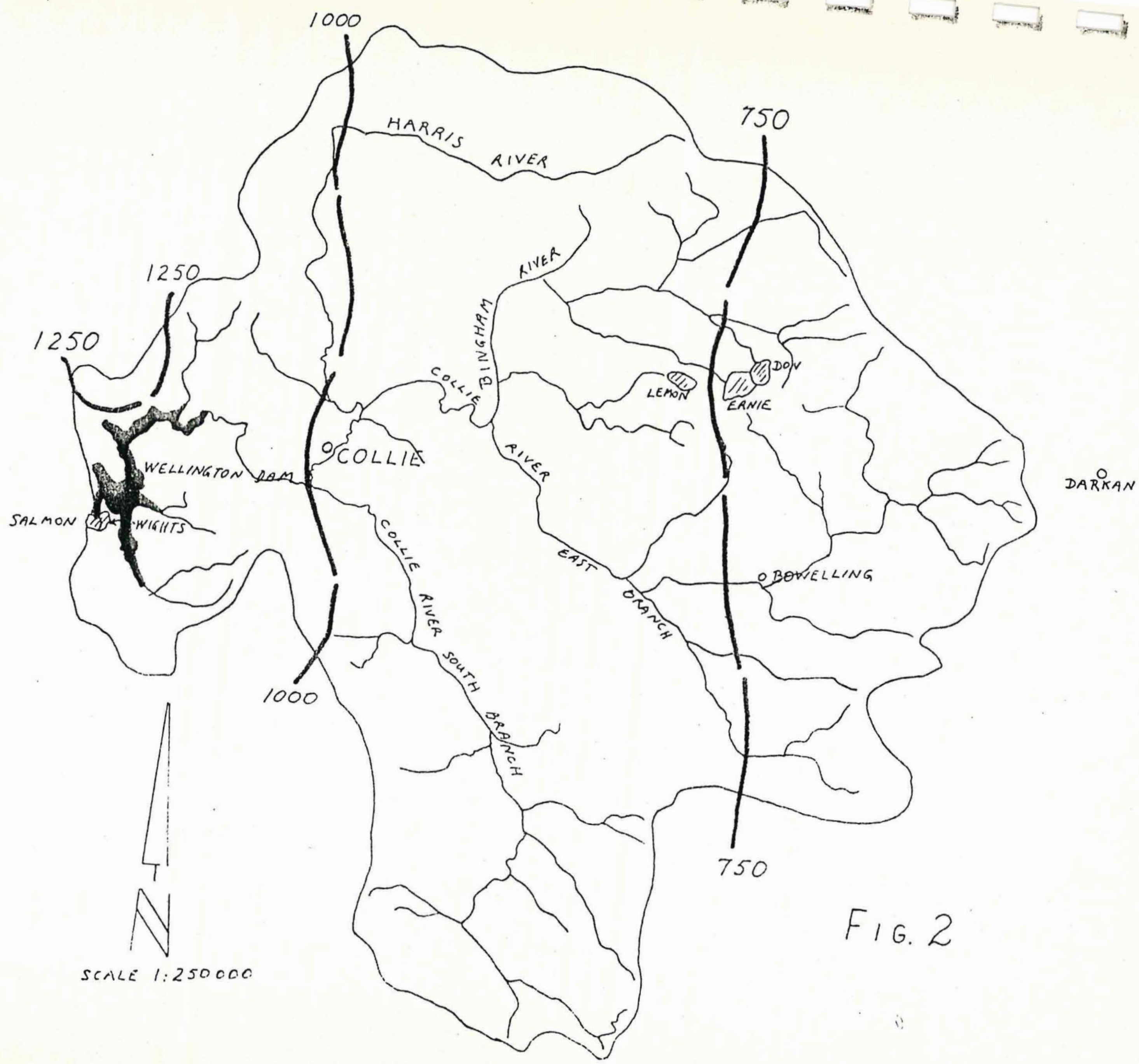

1000
750
HARRIS RIVER
BINGHAM RIVER
1250
1250
COLLIE
DON
LEMON
ERNIE
COLLIE
COLLIE RIVER
WELLINGTON DAM
DARKAN
SALMON
WIGHTS
EAST BRANCH
BOWELLING
COLLIE RIVER SOUTH BRANCH
1000
750
N
SCALE 1:250000

FIG. 2

TABLE 3

TABULATED DATA ON COLLIE CATCHMENTS

Catchment Name	Mean Annual Rainfall (approx)	Approx. Area (ha)	Approx. Relief (m)	Depth of Permanent Water Table at Gauging Site (m)
Ernie	750-800	270	60	14.3
Lemon	750-800	361	70	15.3
Dons	750-800	300	80	9.7
Salmon	1200	81	100	0
Wights	1200	96	100	0

TABLE 4

PWD - CSIRO CATCHMENTS - COLLIE

Wights (Forest) - March 1974 to February 1975.

Rainfall	1396 mm	
Stream flow	322 mm	
Chloride fall	83 kg ha^{-1}	Weighted average 6 mg/l Cl^-
Chloride flow	207 kg ha^{-1}	Flow weighted average 64 mg/l Cl^-

Makes reasonable assumption of no groundwater flow out of catchment other than via stream flow.

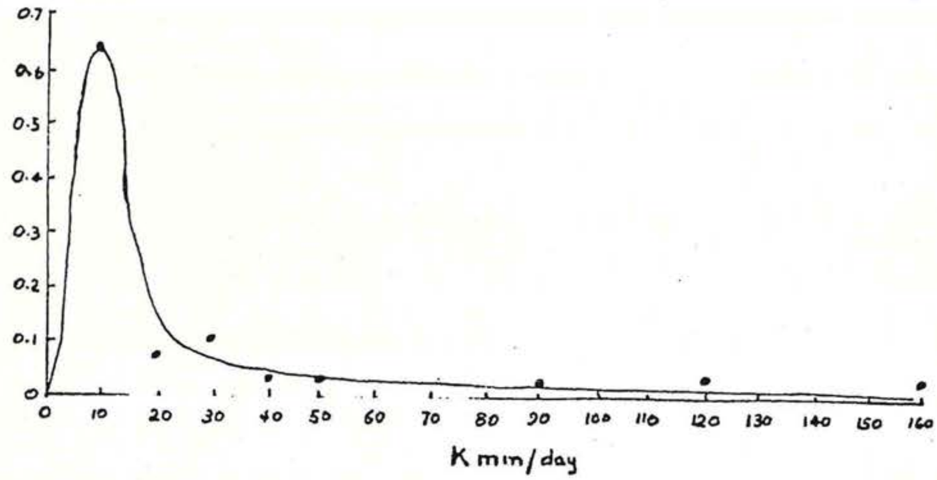
Lemon Catchment (Forest) - March 1974 to February 1975.

Rainfall	975 mm	
Stream flow	51.5 mm	
Chloride fall	43 kg ha^{-1}	Weighted average 4.5 mg/l Cl^-
Chloride flow	14.4 kg ha^{-1}	Weighted average 28 mg/l.

Groundwater flow unknown but measurements being made to obtain flow. Chloride content of groundwaters varies from 100 to 1500 mg/l.

FIGURE 3

FREQUENCY DISTRIBUTION OF HYDRAULIC CONDUCTIVITIES ON WIGHTS CATCHMENT



Battini and Selkirk (priv. comm.) sampled 117 stream sites in the Helena Catchment in 1974 and 1975 and concluded that land use activities had a considerable influence on base flow salinities of small streams. The greatest effects were associated with farm clearing and, in order of decreasing magnitude, with clearing for pine plantations, ringbarking, jarrah dieback and cutting.

(ii) Woodchipping.

The report of an inter-departmental study group in 1974 provided further evidence that changes in land use have caused changes in stream salinity in a relatively high rainfall part of the south-west of the State (Study Group, 1974). Increases in salinity appeared to be associated with clearing for agriculture in areas receiving less than 1,000 mm annual rainfall, while areas receiving more than 1,100 mm annual rainfall appeared to eventually reach a new and lower equilibrium stream salinity after clearing, possibly after 18 to 145 years (Figs. 4 and 5).

Modelling for water and salt balances for the Wilgarup River indicated that agricultural development alone was likely to produce a larger salinity increase than cutting for woodchips, but the two effects would be cumulative.

A more detailed treatment of this report is presented in a paper by Collett later in this Seminar.

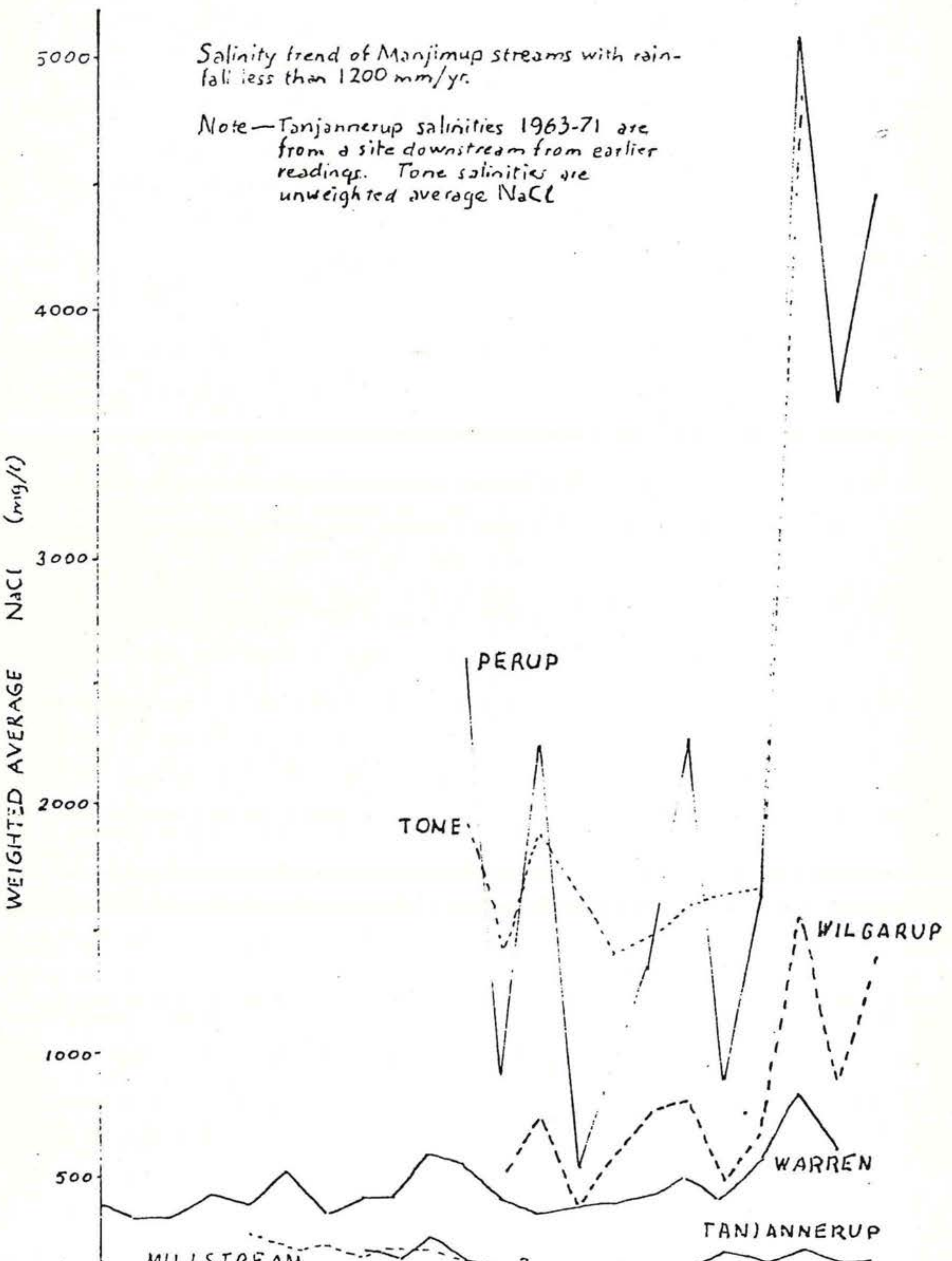
(iii) Bauxite Mining.

In 1975, as part of the inter-departmental efforts to collect and collate background information on salinity in potential bauxite mining areas, a study was conducted to obtain and present information on the land use and salinity history of the Brockman River and the Wooroloo Brook catchments, these being the main portion of the Pacminex Lease area (Frapple, priv. comm.). This report again demonstrated an association between the extent of agricultural clearing and stream salinity - a regression analysis of the limited acceptably recorded data from the Rockman River catchment showed that clearing increases in the Chittering Shire during the period 1963-70 explained 88.8 per cent of the variation in weighted average salinity of the Brockman River.

A further continuing research project is studying variations in stream salinity and the effects of changed land use on stream salinity in potential bauxite mining areas, mainly in the Alwest Lease areas. Results of the work to date suggest a good relationship between stream and river salinity and the extent of agricultural clearing, particularly on the lateritic upland.

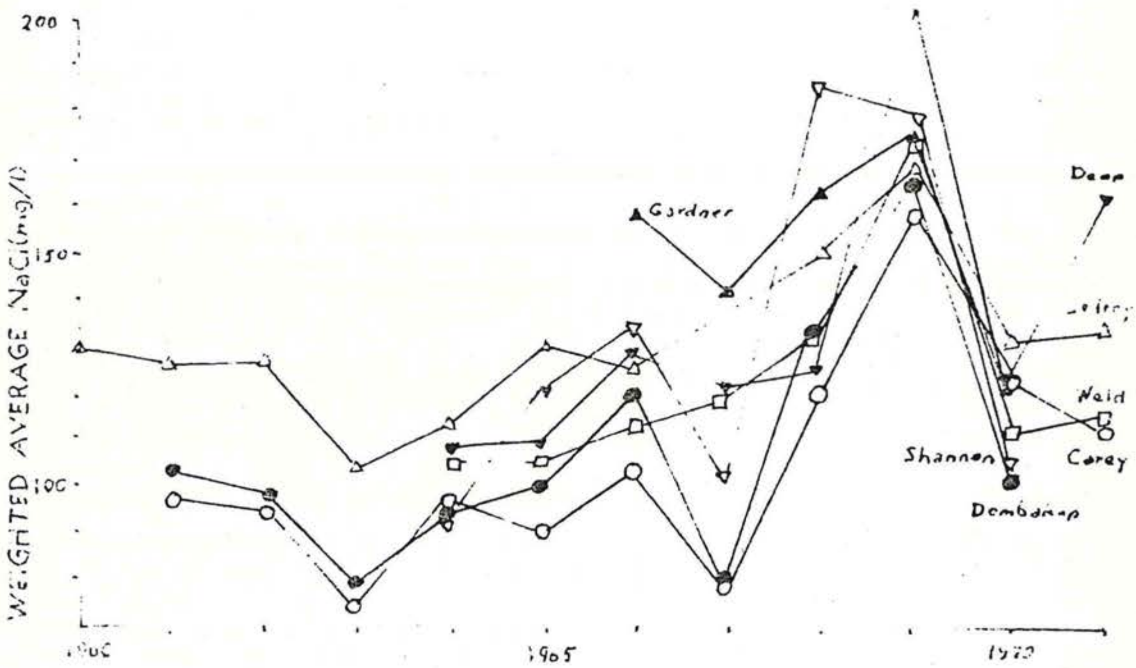
The study is discussed further in a paper by Bestow later in this Seminar.

FIGURE 4



Salinity trend of Manjimup streams with rainfall less than 1200 mm/yr.
Note — Tanjannerup salinities 1963-71 are from a site downstream from earlier readings. Tone salinities are unweighted average NaCl
WEIGHTED AVERAGE NaCl (mg/l)
5000
4000
3000
2000
1000
500
1950
1960
1970
PERUP
TONE
WILGARUP
WARREN
TANJANNERUP
MILLSTREAM
?

FIGURE 5



CONCLUSION

The studies which I have described and which are currently in progress can be expected within the next few years to provide valuable quantification of the changes in the salt and water balances, which occur as a result of clearing of native vegetation for agriculture. In the meantime much data is accumulating which is of immediate application as inputs for modelling purposes (e.g. values for hydraulic conductivity, runoff, depth of wetting, soil salt profiles, stream salinities).

As well as providing information on the adverse effects of clearing for agriculture, the CSIRO-Public Works Department project in particular will provide essential data on the potential for controlling salt release by varying the proportion of land cleared on catchments.

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EFFECTS OF FOREST DISEASES AND PLANTATIONS

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Abstract

Local and overseas studies on the effect of plantation establishment and forest diseases on hydrological balance and water quality are reviewed. The conclusions are related to the local situation, in particular the accumulation of salt in the landscape, and compared with observed facts within the region. Finally, the implication of these conclusions on forest management are considered.

INTRODUCTION

I wish to stress right at the beginning that my evaluation of the hydrological impact of such massive alteration of vegetation as die-back disease and plantation establishment is based on a very mixed collection of studies and observations. Perhaps this is not surprising. We are dealing with perturbations, the amplitude of which probably spans several decades. To be reasonably sure about any conclusions regarding these perturbations, one would need a set of paired catchments, calibrated for a few years prior to the commencement of the perturbations. One would need to follow the impact of the perturbations throughout the entire cycle leading up to the re-establishment of a new equilibrium. Such studies have now been initiated, at least with respect to plantation establishment, but are still at the calibration stage.

That being the case, an alternative approach is necessary. As I lack the necessary skill for mathematical modelling, the best that I can do is to review all available information and string it together into a plausible story. The available information can be put into the following categories.

(a) experimental evidence relevant both topically and geographically,

(b) experimental evidence relevant topically, but from a different geographic region,

(c) other local evidence that has a bearing on the topic.

RELEVANT LOCAL STUDIES

The only study that fits into the first category is the cooperative hydrological investigation of plantation establishment by Forests Department and Public Works Department in eastern Mundaring. Its most serious limitation is that it is only just starting, but ultimately it will replace speculations, such as this one, with factual knowledge. Another cooperative venture, combining the two organizations already mentioned and CSIRO in a study of agro-forestry, is commencing this year in Upper Helena catchment. Both studies will only yield information on the eastern, low rainfall zone, which is the most critical one.

RELEVANT STUDIES IN OTHER REGIONS

It is the second category of information that is probably in best supply. There are quite a number of overseas and Eastern States studies - Zahner (1954), Metz and Douglass (1959), Hewlett and Hibbert (1961), Hallin (1967), Bell and Gatenby (1969), Troendle (1970), Herring (1970), Colville and Holmes (1972), Smith *et al.* (1973) - that deal with hydrological characteristics of broadleaved and coniferous forests and plantations.

On the basis of these one can make the following generalizations:

(a) removal of existing cover leads to reduction in evapotranspiration and increase in either ground water storage or yield,

(b) coniferous plantations have high rates of interception and evapotranspiration, and in winter rainfall climate can ultimately utilize a high proportion of incoming rainfall,

(c) conversion of broad leaved forest to coniferous plantation can therefore increase yield initially, but ultimately the yield will fall down to, or below, the original level.

THE EFFECT OF COASTAL PLANTATION ON THE HYDROLOGICAL BALANCE.

Similar observations are available locally, from the coastal plain. Hopkins (pers. comm.) recorded rise in ground water table following destruction of a pine stand by fire, and the subsequent return toward original level as a new pine stand developed. He also studied the use of water by newly planted pines and concluded that by the age of 3 years the pines had an extensive root system and were utilizing high proportion of the incoming rainfall. Havel (1968) observed that young dense pine plantations had rates of water utilization well in excess of eucalypt-banksia woodland which they replaced, so much so that in years of below average rainfall readjustment occurred through drought deaths. Butcher and Havel (1975) were able to relate the rate of water withdrawal and replenishment to the density of pine stands, and, by experimental reduction of the density through thinning, established an equilibrium resembling that of the native woodland.

Butcher (1976) quantified these observations, and concluded that a dense pine stand intercepted 26 per cent of the incoming rainfall and transpired the remainder during the dry summer. In years of above average rainfall, higher rate of water use and higher pine increment were observed in dense stands, whereas in heavily thinned stands higher rainfall resulted in higher through-put of water to underground aquifers.

THE EFFECT OF DIEBACK DISEASE ON HYDROLOGICAL BALANCE

Virtually no experimental evidence is available, locally or from overseas, on the impact of a major disease such as the jarrah dieback. Although the hydrological impact of the disease is poorly documented, this deficiency can be partly compensated for by reference to other serious disruptions of vegetation. The ultimate effect of the disease is to reduce a tall two storied forest with shrubby ground cover to a savannah woodland with irregular, low open overstorey and ground cover of sedges. This is rather similar to the conversion of a forest to a parkland clearing with ground cover of grasses, except in so far that sedges are perennial, whereas grasses are only annual. This type of perturbation of vegetation cover, in particular its effect on salinity is well documented in the region (Wood, 1924; Lightfoot *et al.*, 1964; Peck *et al.*, 1973). Similarly the more rapid rehabilitation of a deforested area by planting of resistant eucalypts in close stands is not greatly different to rehabilitation of an area mined for bauxite, as it involves mounding and/or ploughing, closely spaced planting and fertilization. This, too, is becoming increasingly better documented (Harley, 1976).

The chief difference between the hydrological impact of the dieback disease, and the more directly man-induced perturbations such as mining and clearing, is that dieback generally acts slowly, and is to some degree selective. However, the basic pattern of reduction in evapotranspiration as vegetation is removed, and increase in evapotranspiration as a vegetation is either rehabilitated artificially or recovers naturally, still holds good. It could in fact be argued that the various perturbations discussed above are merely variants of the same problem which forms a continuum from complete absence of perturbations, through gradual or partial removal of vegetation which characterizes many silvicultural operations and parkland clearing, to sudden and complete removal of all vegetation which characterizes mining, arable agriculture and plantation establishment. Similarly the difference between natural revegetation of cleared, cut-over or disease-affected areas, and their rapid rehabilitation by site preparation, planting and fertilization, is one of a degree rather than of a kind.

THE EFFECT OF PLANTATION ESTABLISHMENT ON WATER QUALITY

The nature and magnitude of the impact varies with environmental conditions. Studies by Batini, Selkirk and Hatch (1976) indicate that on the sandy soils, which appear incapable of storing salt, the increase in through-put of water through soil profile will not be associated with significant adverse rise in salinity of the streams, except perhaps where heavier soils with stored salt are affected downslope.

Such was the case at Mt. Cooke, where the vegetation of a broad upland valley between Mt. Cooke and Albany Highway was strongly affected by dieback. The residual vegetation was bulldozed, the area was ploughed and planted with pines. A portion of the area was given additional experimental treatments such as mounding and fertilization. On the valley floor, only plants planted on the mounds survived, but further up the slope planting was quite successful. At the time of planting, underground water was welling-up under pressure on the valley floor as mud volcanoes. Some pines on the mounds subsequently died, and testing of the groundwater and of adjacent minor stream revealed quite high salinity levels. As the surrounding plantations grew up, the mud volcanoes disappeared, and the valley as a whole dried up. It is possible that predominantly dry years since 1969 have helped, but the change has certainly been most marked.

Similar drying up of upwelling saline ground water occurred in Wellbucket Plantation, which occupies a repurchased grazing property in Upper Helena River. However, the salinity levels of the streams originating in the area still remain high, possibly because portions of the uplands still remain under annual pasture. Relatively high salinities have been observed by Batini and Selkirk (pers. comm.) in streams originating in other pine plantations in the Helena catchment, only some of which occupy former pasture land. It would therefore seem that pine plantations reverse the trend toward higher run-off quite rapidly, but their effect on salinity appears to be more drawn-out. A purely speculative interpretation could be that the root system of pines requires time to fully reoccupy the soil, and in the meantime saline groundwater leaches into the streams. The root system is, in any case, markedly more superficial than that of jarrah, particularly on heavy textured soils.

The two cases so far described refer to plantations in the medium to low rainfall zone (below 1000 mm). Plantations in high rainfall zone (over 1000 mm), such as in the catchments of Brunswick and Harvey Rivers, do not appear to increase salinity to any extent. It is here, however, that problems with increase in turbidity could have been expected, as the high rainfall plantations generally occur on steep slopes with loamy soil.

THE EFFECT OF DIEBACK DISEASE ON WATER QUALITY

An examination of the Public Works Department's 1973 stream data in the light of known catchment characteristics suggests that some of the catchments most affected by dieback (Waterfall Gully, Seldom Seen, Bancell) have high yields which cannot be explained solely in terms of topography, soil and climate. Comparison with similar but dieback-free catchments (Davies) suggests that dieback ultimately results in marked increases in yield. In the western catchment, this occurs without any marked increase in salinity. The increases appear to be very marked, raising the yield from 12 to 20 or even 30 per cent of incoming rainfall (Havel, unpublished data).

The limitation of the above speculations is that Public Works Department data normally refer to catchments of considerable size, and hence comprising wide variation in climatic and edaphic factors. More recent studies by Shea and Hatch (1976) and Shea and Herbert (pers. comm.), which provide short term records of yield and salinity of micro catchments in the Yarragil and South Dandalup catchments, suggest that my speculations, far from being extravagent, are in fact conservative. It appears that tenfold differences between micro catchments in yield and salinity are not unusual, and that the high degree of dieback infection in the western catchments is responsible, at least in part, for their very high yields as compared with the more easterly catchments, in which dieback is either absent, or much more recent and less extensive.

Destruction of vegetation by dieback in some medium rainfall sub-catchments north-east of South Dandalup Dam appears to have also led to an increase in stream salinity. This was also the case in the Mt. Cooke area, mentioned earlier. Fortunately dieback occurrence is so far markedly lower in the eastern, salt-prone zone than in the western relatively salt-free zone.

THE IMPLICATION OF HYDROLOGICAL FINDINGS TO FOREST MANAGEMENT

What implication does this have on forest management? It would appear that dieback is not universally a disaster, at least not from the hydrological viewpoint. In the western high rainfall zone the best treatment of dieback affected sites is probably to do nothing, as the increased yield of water is not negated by increases in salinity or turbidity. To re-establish a dense forest cover would almost certainly result in return to lower yields. It may, in fact, be even desirable to limit the density of natural revegetation by marri, yarri and bullich to relatively open stands. Far more difficult to control will be the spread of phreatic vegetation, in particular tall dense scrub of *Agonis linearifolia*, resulting from higher ground watertable, as its transpiration rates are no doubt very high.

By contrast, the main motive for the re-establishment of dense cover on dieback-affected catchments in the eastern low rainfall zone should be the prevention of rise in salinity of streams, rather than the restoration of relatively meagre timber-producing capacity. The converse of this is that the spread of dieback disease in the eastern catchments would be highly undesirable from hydrological as well as forestry viewpoint (Shea *et al.*, 1975; Havel, 1975).

As for plantations, their future in the northern jarrah region is rather bleak. Clearing, cultivation and the use of weedicides close to reservoirs are rather risky, so that pine planting has been abandoned in the western valleys despite high rainfall and relatively high fertility. On the adjacent uplands, pine planting is handicapped by the strong phosphate-fixing capacity of the lateritic gravels. On the fertile loams of the Blackwood, pine planting can go on without significantly affecting the already high salinity of the Blackwood River.

In the Sunkland, the mediocre soils can be improved by fertilization, and the resulting plantations adjusted by thinning to produce water yields comparable in quantity and quality to native forest, which in any case is already strongly affected by dieback. In the eastern low rainfall catchments, tree planting on agricultural land is highly desirable. However, the salinity risk involved in clearing native forest to establish pine plantation is too great in this zone, and is not justified in light of lower productivity.

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RESEARCH INTO THE EFFECTS OF BAUXITE MINING ON HYDROLOGY

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Abstract

The main objectives of a series of research projects are to facilitate the prediction of any hydrological changes which result from bauxite mining, and the compilation of data which will aid the management and rehabilitation of mined areas to achieve desired land-use objectives.

The hydrologic effects of forest clearing can now be predicted from mathematical and statistical models with reasonable confidence. However the application of these methods to the mining situation takes no account of the effects of rehabilitation to forest, and their predictions therefore err towards the over-estimation of salinity rises. Nevertheless these methods presently indicate that the impact of bauxite mining on water resources in the high rainfall areas is negligible, but that some appreciable salinity rises may result in the medium rainfall zones. The magnitude of this risk remains to be evaluated.

Research into the rehabilitation of mine pits indicates that a wide range of options may be applied to meet land-use and hydrological requirements.

INTRODUCTION

The Hunt Committee

Research into the hydrologic effects of bauxite mining and the means of rehabilitation was initiated by the State Government in 1973 under what has become known as the Hunt Steering Committee. Substantial research into rehabilitation was undertaken by Alcoa, the only presently operating bauxite mining company, prior to that year and indeed is continuing in close collaboration with government sponsored research.

The Hunt Steering Committee includes senior technical representatives of all the government departments concerned with water supply, the environment, agriculture, mines, industrial development and forests. There is also representation from CSIRO and the University of W.A. The Committee thus brings together the best available expertise from many fields and is under the chairmanship of the Chief Engineer of the Metropolitan Water Board.

Objectives

The duties of this Committee come under three headings:

1. To decide what studies, investigations and trials should be undertaken to evaluate the soil salinity characteristics of

the various catchment areas and quantify the predicted effects of mining and re-afforestation on the water resources of the respective catchments.

2. To supervise the research designed to meet these primary objectives and to ensure that the studies are carried out effectively and economically.

3. To use the data resulting from the research to build a framework for the management of bauxite mining to achieve minimal environmental impact.

Hydrological changes

The effects of bauxite mining unfortunately cannot be studied in isolation. They must be identified amongst a number of other factors which are also prone to produce hydrological changes. For example the areas presently being mined by Alcoa are all in State forests in which Jarrah is the dominant tree species. This has not only been cut over for timber production but is also severely affected by die-back disease. Thus the disturbance due to mining may appear to be small in relation to that already produced but can, nevertheless, be additive and may indeed contribute to the spread of the disease in areas not yet affected by it.

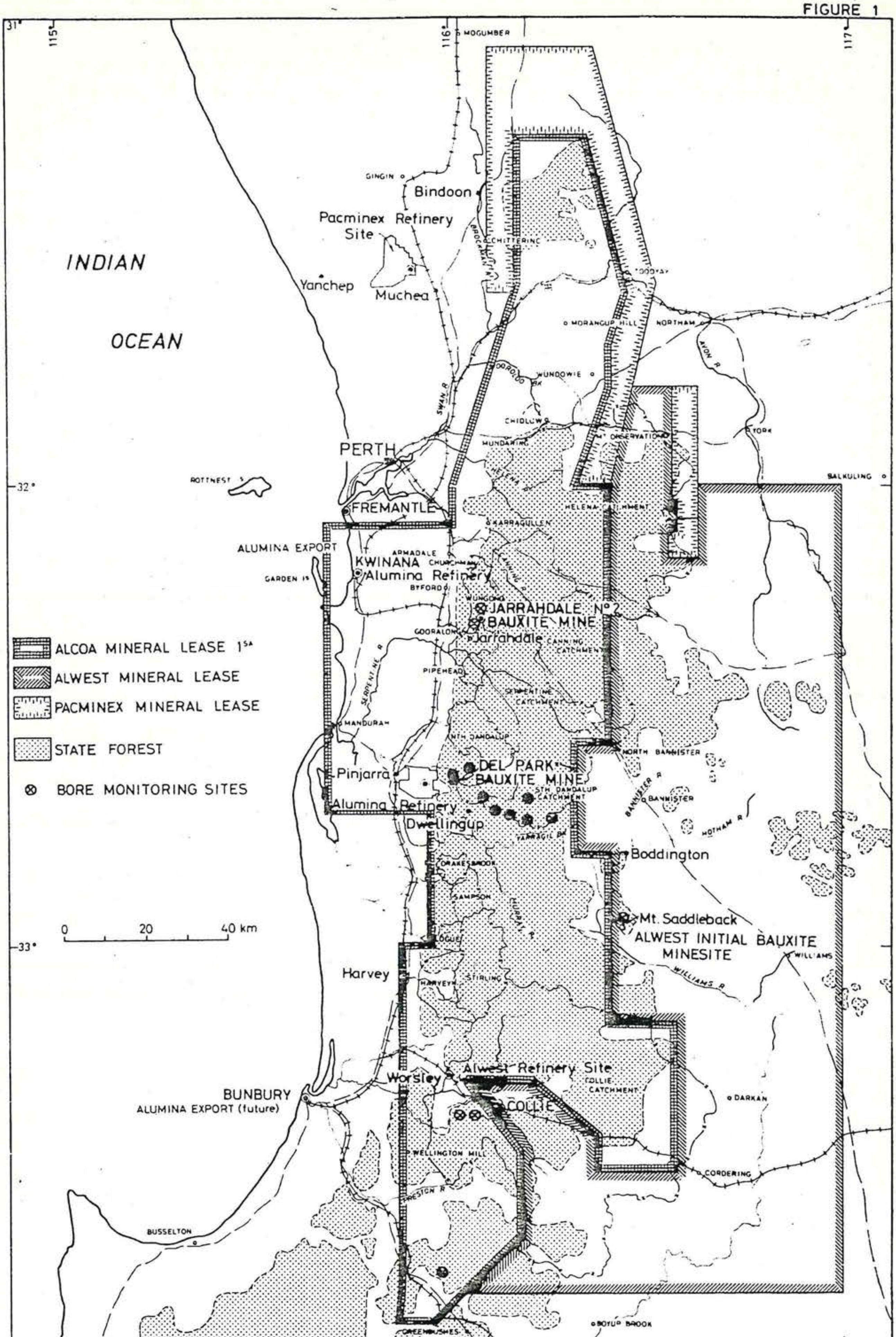
In the Pacminex and Alwest leases substantial areas have been cleared for agriculture (Fig. 1) and so are already subject to massive hydrological changes against the background of which any additional effect may be quite minor.

A general premise in the study of the impact on hydrology of land-use changes is that these changes will be proportional to the area involved. It therefore follows that although a relatively small area of clearing may produce relatively large hydrological changes in the characteristics of the sub catchment in which it occurs, these changes can still be quite minor in the major catchment of which it forms a part. From the point of view of water supplies it is the hydrological change which may take place at a particular point of development, such as a dam, with which public supply authorities are concerned.

BAUXITE MINING

In order to place bauxite mining into perspective in relation to land-use research generally, it is necessary to gain some appreciation of the scale of operations and the areas involved. The Alcoa bauxite mining lease has a total area of 1,055,400 ha (exclusive of the coastal plain) of which 1,328 ha or 0.1% has so far been mined since the inception of mining some 13 years ago. The annual rate of clearing is presently about 200 ha. Mining not only involves clearing forest for mine pits but also includes the provision of haulage roads, conveyor ways and crushing plant sites. The areas given include clearing for all these purposes and may be compared with the total area that is affected by die-back disease of 282,000 ha which is increasing at the rate of 20,000 ha each year.

FIGURE 1



BAUXITE MINING LEASES AND LOCATION OF RESEARCH PROJECTS

In brief the bauxite mining operation at each pit follows a fairly standard sequence. The trees are firstly selectively felled to extract all usable timber, the remaining trees and shrubs are then cleared and fired. The top soil is stock piled and then the bauxite removed by a combination of blasting and ripping. The initial stage in rehabilitation is to batter the steep pit walls, replace the top soil and then deep rip the former floor of the pit. Exotic eucalypts are then planted usually along contour banks.

RESEARCH PROJECTS

General

The Hunt Steering Committee has set up seven projects which have been designed to comprehensively cover a whole range of problems generally related to bauxite mining in the Darling Range but not entirely peculiar to these problems. Thus projects 1 and 2 which deal respectively with the development of simple and more complex mathematical models to forecast the impact of bauxite mining on stream salinity may be applied also to many land-use change situations involving modifications to the plant population. The application of the mathematical models to the bauxite mining situation is dependent on the collection of data by other projects.

Projects 3 and 4 involve monitoring the changes in groundwater regimes which result from mining. The former was designed to monitor the post-mining situation to provide early data related to post-mining whereas Project 4 was intended to monitor firstly the relatively undisturbed situation prior to mining, next the impact of mining, then the rehabilitation phase. This is a long term project. Project 6 is a paired catchment study in which mining takes place within one catchment whilst the other is left unmined as a control. It is essentially a comprehensive study in that it involves monitoring both surface and groundwater, it also is a long term study.

Project 5 involves the study of rehabilitation methods of both the mined and associated service areas. A wide variety of options involving different engineering techniques, plant species and indeed alternative objectives are under trial. These range from the establishment of forest plantations to annual pastures.

As many of the projects are quite long term and expected to last several years, the identification of areas which might be at risk to adverse water quality changes is regarded as a matter of some urgency. Project 7 attempts to do this by the application of statistical methods to relate the base flow salinities in agricultural areas to patterns of clearing.

Review of Research

In the review of research which follows, it is not possible to present the data so far collected or even to comprehensively survey it all here. However all projects have already yielded information from which quite important conclusions may be drawn and some of this will be referred to subsequently.

It should be mentioned, by way of acknowledgement, that about 30 specialists have been involved in the work of the projects and that these come from all of the authorities represented on the Steering Committee and Alcoa. It should also be recorded that Alcoa has done much of the borehole drilling for data collection.

Projects 1 and 2: The development and application of productive mathematical models

A relatively simple model has been used to predict increases in flow weighted average stream salinities consequent upon clearing and mining. This is based on the supposition that stream flow may be regarded as consisting of two components: overland flow or direct run-off, and base flow or the groundwater contribution. Additional infiltration to groundwater which results from the removal of vegetation and hence reduction of evapotranspiration, is raised to the salinity of the groundwater contribution by the leaching of salt stored in the soil profile, and appears as additional stream base flow.

Although this represents a great simplification of the complex relations between groundwater and stream flow and ignores the time delays which must exist between the accession of additional recharge and its discharge to streams, it nevertheless provides a useful tool. So far it has only been applied to clearing and so no account is taken of the hydrologic changes consequent upon rehabilitation which includes replanting forests. Conclusions based on its application to the mining situation which includes this type of rehabilitation may therefore err towards the pessimistic in that they may indicate larger salinity increases than would occur in practice.

As a result of the application of the model it is possible to draw a number of important conclusions:

(i) Bauxite mining in high rainfall areas can be expected to have a negligible effect on the salinity of small head-water streams such as those in the vicinity of Jarrahdale and Del Park. In consequence any effects on major catchments will be virtually undetectable.

(ii) Measurable increases in salinity of some local streams are predicted in the intermediate rainfall areas such as the Yarragil and Chalk sub-catchments. The impact of these increases on the outflow of the major catchment is dependent on the overall proportion of that catchment that is mined and the efficiency of rehabilitation.

(iii) Mount Saddleback lies in a low rainfall area and there is little doubt that clearing for mining will produce appreciable increases in the salinity of small streams. These make only small contributions to flow in the Hotham and Williams rivers whose catchments are already largely cleared for agriculture and hence are the subjects of massive hydrological change. Any added influence by the effects of mining would be quite small.

Project 3: Changes in Groundwater hydrology and salinity after mining.

Grids of bores have been drilled over three mined areas to define the groundwater system and its response to mining and rehabilitation. As the elapsed time since initial re-vegetation differs from site to site, the time relations in the response of the groundwater system can be assessed.

1. Del Park.

Twenty bores were drilled in a 5 by 4 grid covering both the mine pit and the adjoining forest on the northern flank of a tributary valley to the Boomer Creek. Four of the bores were cored and the cores analysed to determine their density, salt and water contents. The bores were installed with slotted plastic tubing for the measurement of water table levels.

Mining was completed in December 1972 and the pit area was re-planted with *Eucalyptus resinitera* and *E. saligna* by June 1973. The groundwater configuration in the pre-mining situation is unfortunately not known, but as the original topographic contours run east-west it is a rational but unproven assumption that the water table sloped uniformly southwards. When the bore water levels measured in August 1974 are contoured they show that a groundwater mound has built up below and immediately downslope of the pit (Fig. 2). The subsequent seasonal fluctuations of the water table and the measurement of groundwater salinities have been used to arrive at an approximate water balance for the year, nearly two years after mining took place. This indicates the following:

(i) The net recharge below the mine pit is between 21 and 34% higher than below the forest.

(ii) Groundwater discharge from below the mine pit is two to three times that of the groundwater discharge from below the forest. This is due to a lack of transpirative draw once water has reached the water table.

(iii) The release of salt from the unsaturated zone in the mine pit is small but leaching is taking place in the zone of water table fluctuation. The same may be occurring below the forest.

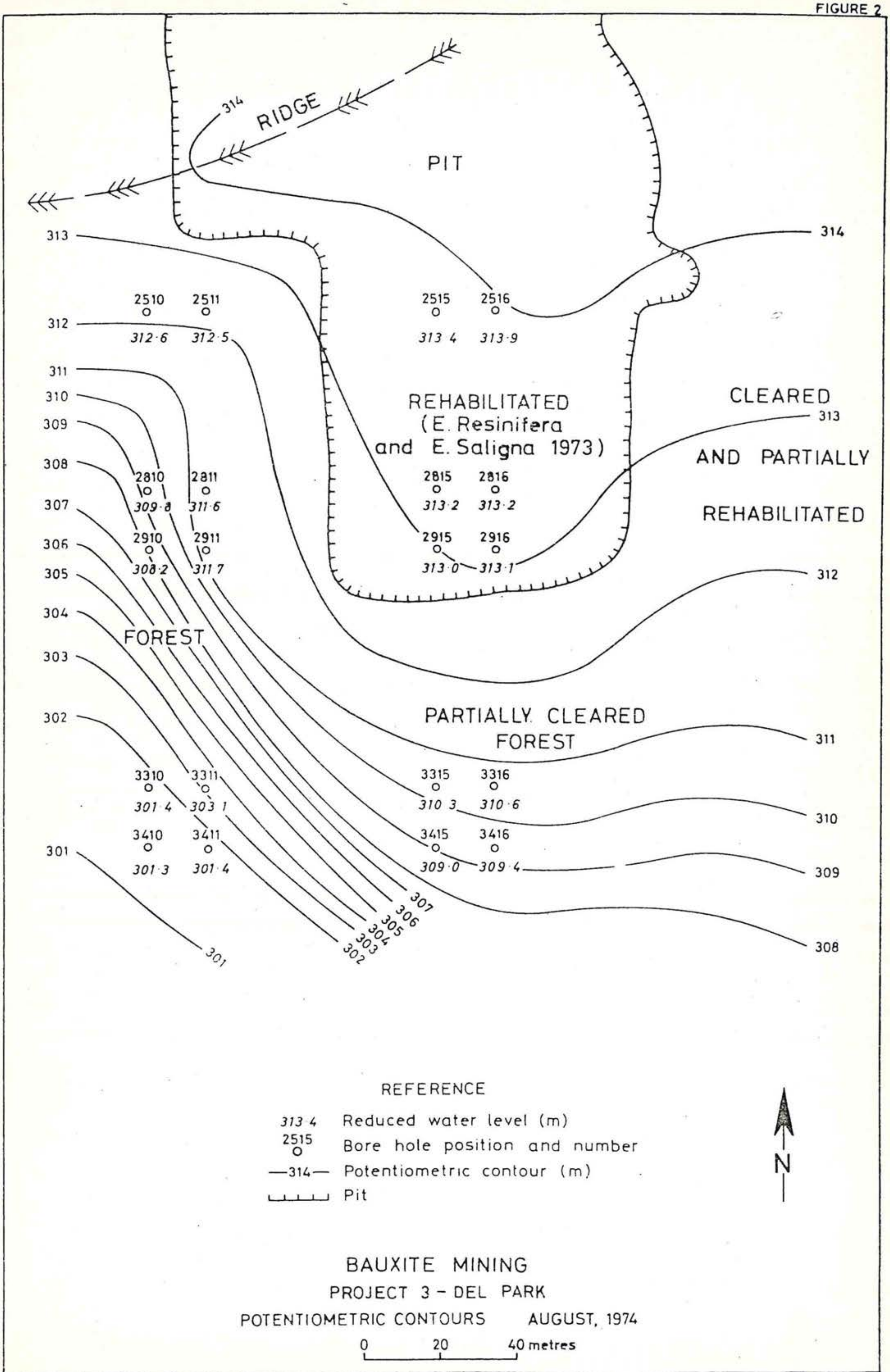
(iv) The present salt unbalance is such that 22% more salt is being discharged down-slope of the pit than is received in rainfall.

(v) Although there is salt leaching taking place below the mine pit the lack of transpirative loss from the water table means that the additional salt is discharged in a larger quantity of water and hence is diluted to a salinity that is now lower than that of the main body of groundwater.

2. Jarrahdale Mine Site, Location 5.

Mining in the western pit at the Jarrahdale mine site was completed in July 1971, and re-planted with *Eucalyptus microcorys* by July 1972. In the eastern pit mining was finished by June 1970 and was re-planted with *E. globulus* by July 1972. Water level measurements in the twenty auger bores and cored holes that were drilled in June 1975 indicate that the eastern pit has a somewhat subdued groundwater

FIGURE 2



BAUXITE MINING

PROJECT 3 - DEL PARK

POTENTIOMETRIC CONTOURS AUGUST, 1974

15876

mound below it but that the western pit may actually have a slight groundwater trough below it. This difference in the groundwater configuration is probably because the *E. microcorys* stand is far more advanced in growth than the *E. globulus* so that its transpiration is much higher.

3. Langford Park.

Mining was completed in May 1968 and the pit was planted with *Pinus pineaster* by July 1969. Between September and November 1975 eighteen auger bores and 2 cored bores were drilled and when water levels were measured and contoured they indicate the existence of a groundwater trough below and downslope of the pit (Fig. 3).

Summary

Apart from the conclusions already mentioned in connection with the Del Park study it is possible to add another which has important implications for post-mining management. This is that the groundwater mound which represents an increase in the groundwater storage and the mobilisation of some stored salt is built up rapidly immediately following clearing and mining, and that it may be depleted within 6 years as re-planted forest matures. Its transpiration both reduces the accession of water to the water table and withdraws water from it.

Project 4: Monitoring groundwater before, during and after mining.

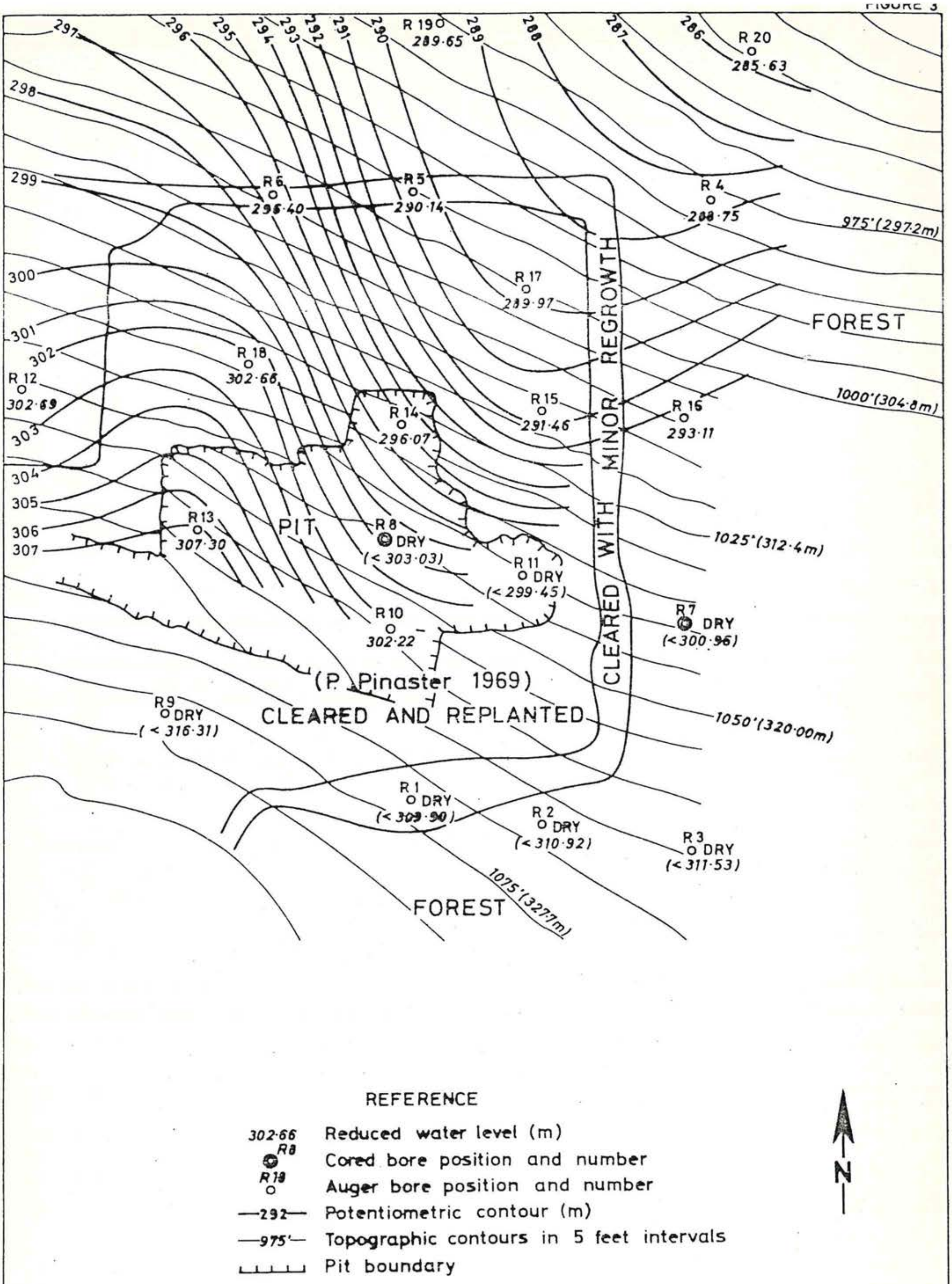
Eight sites north and east of Dwellingup and a site east of Kirup have been included in a long-term groundwater study of future bauxite mining areas. Both core and auger holes have been drilled in areas which experience a range of rainfalls and are situated in differing landforms. The main areas of study include the Huntly mine site in the high rainfall jarrah/marri forest, similar to the Project 3 mine sites and a transect through to die-back free medium rainfall jarrah forest.

Not all of the planned grid drilling has yet been completed so that the most important data that have so far been gathered from this project have been provided by the cores which have been analysed to derive salt storage figures. These together with similar analyses from Project 3 indicate that salt storages are low in the high rainfall zones and that the greatest values generally occur in the uppermost ten metres of the soil profile and are well above the position of the undisturbed water table.

Comparison between the salt storage figures for the different areas indicates a trend towards increase in an easterly direction and it is evident that most of the stored salt is in fact sodium chloride. Some work at Huntly and Kirup as well as modelling studies at Del Park suggests that not all the salt in storage is necessarily mobilised as a result of clearing which could imply that some groundwater may flow along preferred paths both in sub-horizontal and vertical directions.

The mining of bauxite necessarily includes the removal of the salt that it contains and this is therefore no longer available for mobilisation.

FIGURE 3



BAUXITE MINING

PROJECT 3 – LANGFORD PARK

POTENTIOMETRIC CONTOURS DECEMBER, 1975

0 20 40 60 metres

15879

Project 5: Rehabilitation.

The rehabilitation of bauxite mine pits has three primary objectives:

1. To restore the area to the desired land use.

2. To minimize run-off scour and erosion and hence keep stream turbidity to a minimum.

3. To satisfy the hydrological needs of the site. These include taking measures to keep any stream salinity increase to a minimum. They may include the maximisation of run-off if the land use objective is primarily that of water catchments. At the other extreme it may be desirable to maximise the transpiration use in order to minimize infiltration which might increase salt yields to base flow.

4. To inhibit, so far as possible, the spread of the fungus causing die-back disease (*Phytopthora cinnamomi*).

The sequence of procedures involved in mining and rehabilitation has already been outlined. One aspect of research into rehabilitation has been directed to improving current practice which has the land-use objective of re-establishing forest. However, previous concentration on tree planting rather than early ground cover has resulted in costly emergency measures to control run-off from high-intensity rainfall. Investigations are showing that the replacement of 5 cm of new top soil results in adequate ground cover after about three years. Native legumes may be seeded and not only improve soils but may inhibit the spread of die-back. Direct seeding with tree species is being included in experimental treatments to reduce erosion in newly rehabilitated areas.

Deep ripping to assist root penetration of the former mine floor has been regarded as essential for good tree growth and to avoid the wind-throw which affected early non-ripped plantings. Investigations are being made into reducing the amount of ripping which is an expensive operation and into the hydrological effects of varying the planting density best suited to timber production, flora and fauna conservation and aesthetics.

In current work two further associations are being compared with the current practice of establishing closed, regular, formations of a single tree species. These are:

(i) open woodland or parkland formations including shrubs and clover ground cover.

(ii) mixed tree species in forest formations and having a random distribution with understory species.

The methodology now exists to rehabilitate mine pits in a variety of ways to meet most objectives in the higher rainfall areas. However there are two areas where further study is required. The potential exists for a mining operation to spread forest disease and the best means of combating this still needs to be found. Early study is needed to assess the efficiency of the known methods of rehabilitation in the drier areas particularly in countering the greater salinity risk.

Project 6: Paired Catchments.

This project, which is an essentially long term one is designed to provide comprehensive data on the run-off yield, turbidity, salinity, sediment load, climate, water table fluctuations and groundwater salinity. So far 15 bores have been drilled on each of two catchments in the Mt. Saddleback area, climate and stream gauging stations have been installed and a start made with the collection of a full range of data.

This project was primarily initiated by the Steering Committee to cover the Alwest lease area and priority was given to Mt. Saddleback as this was most likely to be mined as soon as Alwest went ahead. It is expected that several years monitoring will be possible in both catchments prior to the initiation of mining in one of them. This will provide base line data including variations in annual and seasonal rainfall patterns.

Further paired catchments are desirable in the intermediate rainfall zone where data from Project 4 indicate the presence of significant amounts of salt. There is every possibility that a further catchment pair will be established in the summer of 1976/77 in or close to one of the easternmost Project 4 areas.

It is obvious that to meet the objectives of Project 6 in the low to intermediate rainfall area, mining must take place on one of each pair of catchments after the calibration period of 3-5 years. To a degree it may be possible to simulate the mine procedures by clearing and possibly stock-piling ore but the complete hydrologic effect cannot be assessed without also including rehabilitation.

Project 7: Identification of areas vulnerable to salinity change.

The application of statistical analysis, particularly regression equations to stream salinity data, land and land-use parameters has been particularly successful. In predominantly forested catchments most of the variation in stream salinity is accounted for by clearing and annual rainfall. In the lower rainfall farmed and part forested catchments, predictions of salt flow can be made based on the proportion of land cleared and the proportion of cleared land which is laterite-capped upland. Areas in which these relationships have been established are situated on the tributaries of the Bannister, Murray, Hotham and Williams rivers. Other cleared or part-cleared catchments that have been studied are the Brockman and Wooroloo catchments within the Pacminex lease area. Here a strong correlation has been established between agricultural clearing and stream and soil salinity.

Calculations based on the assumption that bauxite mining and agricultural development are similar in their hydrologic effects show that salinity increases in the two rivers, due to mining, should be small in relation to that already caused by agriculture. Even small increases are not necessarily tolerable of course, and the unqualified application of regression analyses to predict the effect of bauxite mining would tend to give a pessimistic result. This is in the sense that it is probable that rehabilitation and careful catchment management will alleviate any hydrologic effects within a relatively short space of time.

One of the objectives of the research has been to arrive at the cheapest means of predicting the magnitude of salinity changes particularly using base flow salinities both in the Project 1 model and by the use of regression equations. Independent studies in the Helena and Yarragil areas indicate that baseflow salinities underestimate actual groundwater salinities. This may indicate the need either for a re-definition of base-flow or accepting the fact that within a given catchment, groundwater salinities will never be uniform. There is also a need in research to relate soil salt storage to groundwater salinities. It is hoped that some of these questions will be answered when further data are available from the drilling which remains to be done at Dwellingup, Collie and Mt. Saddleback.

SUMMARY AND CONCLUSIONS

Both mathematical modelling (Project 1) and the application of statistical correlation (Project 7) can be used effectively to predict the salinity changes in streams due to clearing. The equations may be proved in areas having adequate data and then be used in areas of different rainfall and salt storage. However when they are applied to clearing and mining with rehabilitation verification is still required as the predicted salinity changes may be greater than would actually occur.

Present predictions indicate that salinity increases in the high rainfall areas will be negligible and that mining in the low rainfall areas would produce salinity increases in local streams at least in the short term, but this would cause negligible effect in the major rivers whose salinity is increased by the effects of agricultural clearing. Doubt remains as to the precise impact of mining in the intermediate rainfall zones.

The actual effects of bauxite mining on groundwater hydrology which are being monitored in Project 3 include the build-up of a groundwater mound below the mine and that this can be dispersed by rehabilitation with sufficiently dense forest stands.

Infiltration and run-off are subject to change with differing engineering treatments in the mine pit rehabilitation process. Thus in higher rainfall areas contour banking and deep ripping are aids to the control of erosion and stream turbidity in that they reduce or impede run-off. However such practice may be undesirable in areas of lower rainfall where additional infiltration may mobilise the greater salt storages. In the higher rainfall areas management for increased run-off to achieve maximum water yield may be a desirable objective. However, turbidity would have to be controlled by the early establishment of a ground cover of shallow rooting annual plants and native legumes.

Any adverse hydrologic effects that are produced directly by mining and of course the provision of ancillary services such as roads and conveyor ways will be compounded by the increased spread of die-back in areas where it does not already occur. Research is needed into the best means of minimizing its spread in the mining situation.

It is evident that quite a wide range of options exists in the rehabilitation of mine sites. These are capable of meeting a variety of land use objectives.

It is important that the long term objectives be established early before mining actually takes place. This naturally involves a decision as to which alternative is required. The choice lies between water supply catchment, timber production, amenity and recreation or agriculture. Decisions with respect to particular mine pits need to be made in the overall context of land-use planning for the region as a whole and this is where clearly defined objectives are needed.

RESEARCH INTO THE EFFECTS OF THE WOOD CHIP INDUSTRY

D.B. Collett

Public Works Department, W.A.

Abstract

To demonstrate and predict the effect of the wood chip industry in the south west of Western Australia on the present and future water resources of the area, four research projects are being carried out. Early results indicate that the area of highest hazard for salinity increases in streams, is in the lower rainfall sections of the Wood Chip License Area, but it is too early in the life of most projects to indicate firm conclusions. The research being carried out is described and some of the early results are presented.

INTRODUCTION

Research into the effects of the wood chip industry on the water resources of the area is required by the Environmental Protection Authority and was arranged under a similar hierarchy to that used for research into the effects of bauxite mining.

A Steering Committee comprising nine members drawn from seven State Government Departments and CSIRO determined that four avenues of research were required, and arranged that the work be carried out under the supervision of four supervisory panels. The actual work in turn was carried out by workers drawn from a number of Departments and CSIRO. A diagram of the hierarchy is shown in Fig. 1.

The research programme is a cooperative effort by four State Government Departments and CSIRO and this paper is in essence a summary of work carried out by the multi-disciplinary groups of scientists, foresters, agriculturalists, geologists, engineers and hydrographers.

Much of the following has been extracted from reports by the supervisory panels and working groups.

LEVELS OF RESEARCH

The research was cast at three levels to provide results at three different positions in time.

1. To give immediate results.

   As the wood chip industry was about to commence, some immediate indication of likely effects on water resources was required although it was appreciated that such results could not be expected to be very precise or provide absolute proof.

   Project 1 falls into this category.

RESEARCH INTO THE EFFECTS OF THE WOODCHIP INDUSTRY

KELSALL STEERING COMMITEE

PUBLIC WORKS DEPARTMENT	K.J. KELSALL — CHAIRMAN
PUBLIC WORKS DEPARTMENT	D.B. COLLETT
FORESTS DEPARTMENT	E.R. HOPKINS
MINES DEPARTMENT	J. LORD
DEPARTMENT OF AGRICULTURE	T.C. STONEMAN
DEPARTMENT OF CONSERVATION AND ENVIRONMENT	M. MULCAHY
METROPOLITAN WATER BOARD	I. O'HARA
DEPARTMENT OF INDUSTRIAL DEVELOPMENT	J.V. CROSBY
C.S.I.R.O.	A.J. PECK

PROJECT 1

IDENTIFICATION OF AREAS VULNERABLE TO SALINITY INCREASE

STUDY GROUP

T.C. STONEMAN (CONVENER)	AGRICULTURE DEPT
P.R. GEORGE	" "
M. JAMES	" "
C.V. MALCOLM	" "
A.B. HATCH	FORESTS DEPT.
B.J. WHITE	" "
T.T. BESTOW	MINES DEPT.
H.C. HUGHES	GOVERNMENT CHEM. LABS.
K.L. BARRETT	PUBLIC WORKS DEPT
J.E. DAVIS	" " "

PROJECT 2

PAIRED CATCHMENT STUDY

SUPERVISORY PANEL

D.B. COLLETT (CONVENER)	PUBLIC WORKS DEPT
K.L. BARRETT	" " "
E.R HOPKINS	FORESTS DEPT.
T.T BESTOW	MINES DEPT.
W.M. McARTHER	C.S.I.R.O.
A.J. PECK	"

PROJECT 3

MONITORING AT STREAM GAUGING STATIONS

SUPERVISORY PANEL

D.B COLLETT (CONVENER)	PUBLIC WORKS DEPT
K.L. BARRETT	" " "

PROJECT 4

MONITORING OF GROUND WATER HYDROLOGY

SUPERVISORY PANEL

E.R. HOPKINS (CONVENER)	FORESTS DEPT.
T.C. STONEMAN	AGRICULTURE DEPT.
D.B. COLLETT	PUBLIC WORKS DEPT.
T.T. BESTOW	MINES DEPT.
A.J. PECK	C.S.I.R.O.

FIG 1

2. To give short to intermediate term results.

   Project 4 was designed to give more definite evidence of effects during the early years of the wood chip industry.

3. To give conclusive long term results.

   Projects 2 and 3 were designed to provide firm hard data, which should show fairly conclusively the effects of the wood chip industry, but they could take up to ten years or even more to complete.

PROJECT 1: Identification of Areas Vulnerable to Salinity Increases.

Project Description.

Under this project, the history of land development and salinity problems in the Wood Chip License Area were examined using as much data as the researchers could locate, and from this data they derived indications as to possible effects of the wood chip industry on stream salinity.

Results.

Project 1 was completed in June 1974 and the Working Group's findings were published in the Department of Agriculture Technical Bulletin No. 27 "The Influence of Land Use on Stream Salinity in the Manjimup Area, Western Australia".

As the findings of this project are covered quite fully in this publication, there is no need to include details here, but the following "Conclusions" extracted from this report are relevant:

Conclusions.

A review of the history of land use and stream salinity in the marri wood chip License Area in the Manjimup district of Western Australia has been made. There is a general paucity of data for years before 1940, but sufficient was obtained to allow general trends to be clarified and areas of particular concern to be pin-pointed.

Statistics for land use show that major land use changes from forest to agriculture occurred before 1929. Subsequent changes have involved cleaning up the initial 'clearing', a surge of clearing in the driest parts of the Tone River catchment since 1945 and a general overall increase of about 10 per cent since the late 1920's.

Forestry methods have changed from exploitation as a preparation for agriculture in the early days, to cutting programmes aimed at long term forest improvement and production.

There is evidence that changes in land use have caused changes in stream salinity in the License Area. For two part-cleared catchments, East Brook and Lefroy Brook, receiving 1260 and 1320 mm/a average rainfall stream salinity levels indicated by available data are below

200 mg/ℓ NaCl. An early but low peak in salinity probably occurred following clearing in about 1913 and there is evidence of a drop in salinity to a new equilibrium for East Brook.

By contrast, for a part-cleared catchment (Wilgarup River) receiving 1000 mm/a average rainfall, there is evidence of considerable increases in salinity.

Modelling of water and salt balances for the Wilgarup River catchment indicates that if all alienated land is cleared for agriculture or if 5000 ha of forest is cut for wood chips the weighted average stream salinity is likely to increase. Agricultural development alone is predicted to produce a larger increase than cutting for wood chips but the two effects are cumulative.

Further studies of the salt and water balances of streams in 1000 to 1200 mm/a rainfall zones should be made and an attempt should be made to study the integrated effect of all possible clearing and wood chipping on the Warren River. Salt and water balance studies do not suffer the serious time limitations of monitoring programmes as they can be based on current data.

Rivers with mean catchment rainfall less than 1200 mm/a and significant areas of uncleared alienated land in their catchments are the Donnelly, Wilgarup, Perup, Tone and Warren. Of these the Donnelly, Wilgarup, Perup and Warren have appreciable areas which could be subjected to cutting for wood chips. In addition, the Deep River catchment has significant areas of possible cutting for wood chips but an insignificant area of alienated uncleared land and a mean rainfall of 1180 mm/a.

It is most unlikely that cutting forest for either wood chips or agricultural development will cause a significant change in the salinity of the Carey, Fly, Treen, Lefroy, Dombakup, Shannon, Gardner and Weld Rivers.

The possible vulnerable area from the point of view of the wood chip project can therefore be narrowed down to those parts of the catchments of the Donnelly and Warren rivers receiving less than a rainfall level somewhere between 1000 and 1200 mm/a. (The Wilgarup and Perup rivers are in the drier section of the Warren catchment.) The Deep River can probably be excluded on the basis of high rainfall, and for the other rivers agriculture on uncleared alienated land represents a greater hazard per unit area than cutting for wood chips. Cutting of wood chips on private land as a preparation for agriculture may represent a hazard.

Multiple regression analysis of catchment parameters relative to stream salinity offers a useful means of rating the factors contributing to stream salinity. With refinement the regression equation may be useful for predicting changes in stream salinity following clearing.

PROJECT 4: Monitoring of Groundwater Hydrology.

Project Description.

This project is designed to study changes in groundwater hydrology from the pre-cutting state, through logging, and into the regeneration phase.

By measuring water level and salinity changes in bores through this cycle, it should be possible to predict any likely changes to the salinity of stream flow, and by selecting study areas which will be logged early in the history of the wood chip industry, relatively short term results should be forthcoming.

If, for instance, the underground water is saline, and cutting causes a rise in water tables, which do not recede during regeneration, stream flow salinities can be expected to rise.

Conversely, if the underground water is fresh, and there is no permanent rise in water tables, the salinity of stream flow is not likely to be adversely affected.

In addition, to determine the amount of salt stored in the soil profile, cores taken during the course of drilling the monitoring bores were analysed for salt content.

It follows that rises in water tables where the soil profile contains large quantities of salt could mobilize this salt and allow it to move into a stream, causing a salinity increase, whereas there would be little hazard where the amount of salt stored in the soil profile is low.

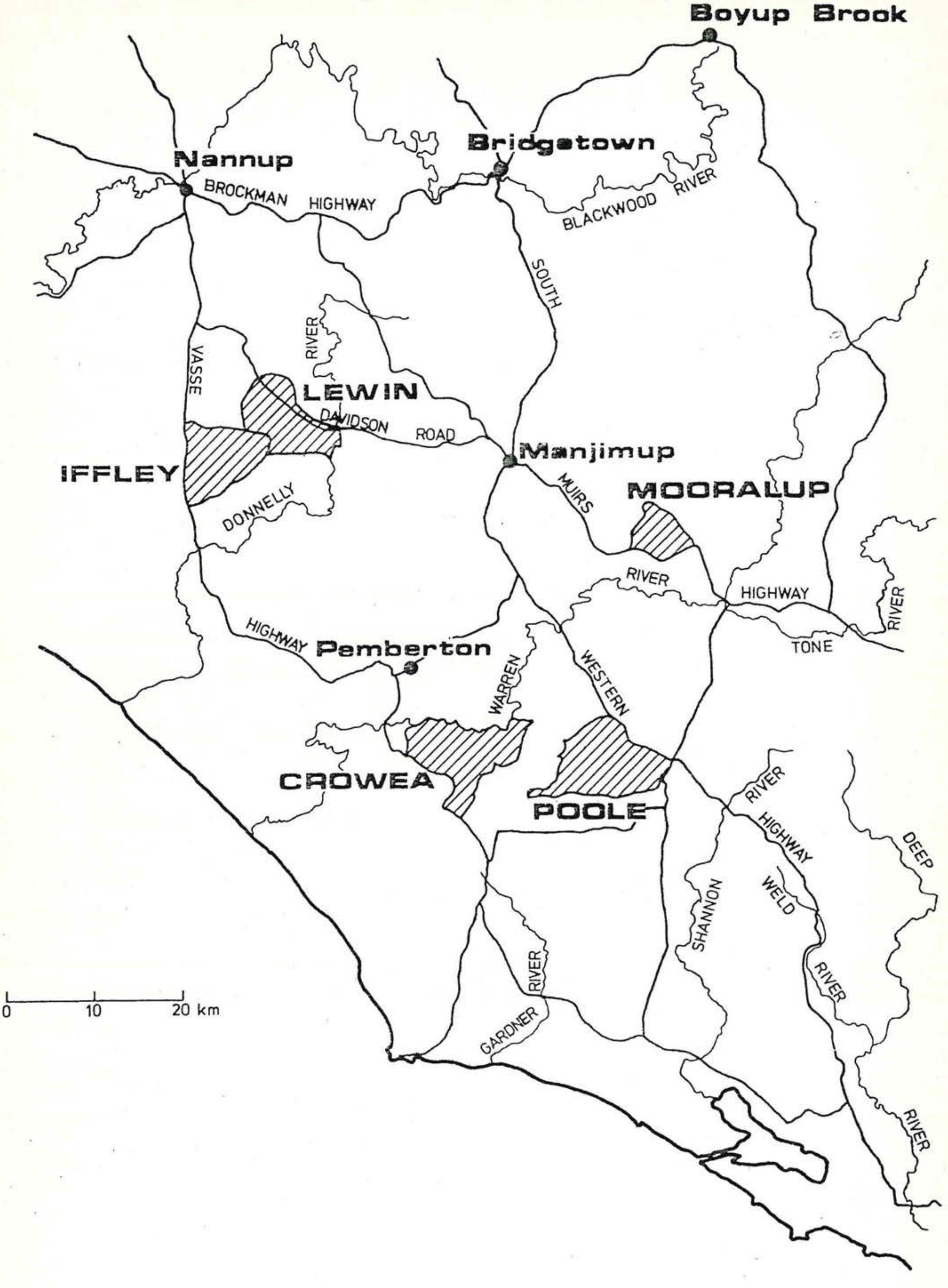
Study Areas.

Five areas were selected to sample the rainfall-forest type combinations representative of the forest involved in the wood chip project. In each case the selection included an entire sub-catchment of a major drainage system in order to sample the complete range of topographical situations from ridge top to valley bottom. The spatial arrangement of the five sampling coupes is depicted in Figure 2 and the following brief descriptions illustrate the range of rainfall, soils and forest type involved.

Crowea Coupe - High rainfall Karri/Marri. Estimated rainfall 1400 mm/annum. Soils predominantly red earths grading to podsols on the upper slopes. Karri forest is almost pure on the red earths, grading to a small area of jarrah/marri on the ridges.

Poole Coupe - Medium rainfall Karri/Marri. Estimated rainfall 1200 mm/annum. Soil and forest types follow a similar pattern to Crowea but the topography is flatter.

Iffley Coupe - High rainfall Jarrah/Marri. Estimated rainfall 1250 mm/annum. The area has extensive lateritic soils with small pockets of red earths at lower elevations. The forest is



LOCATION OF RESEARCH COUPES PROJECT 4

FIG 2

dominated by jarrah throughout. This coupe is situated on the ill-defined escarpment separating the south west plateau from the sunklands association.

Mooralup Coupe - Medium rainfall Jarrah/Marri. Rainfall 860 mm/annum. A steep catchment draining into the Wilgarup River. No stream bed and most water flow appears to be sub-surface. The entire area is jarrah/marri forest with a dense undergrowth of shrubs typical of semi-wet sclerophyll forest. The dense shrub layer in a 860 mm rainfall suggests that the surface soils are very retentive of moisture.

Lewin Coupe - Medium/high rainfall estimated at 1150 mm/annum. Mainly jarrah/marri, with a small area of karri confined to a narrow strip on the valley floor. This type is typical of large areas in the north west of the chip wood license area.

The sample range does not include representation of low rainfall jarrah forest present in the license area but temporarily excluded from chip wood cutting. This type or zone is being covered in detail by a paired catchment study of Project 2 which will yield information within an acceptable time period.

Groundwater Bores.

Ten bores were drilled in each coupe on a grid pattern as indicated on the diagrem below Table 3, and to provide a control, two additional bores were located adjacent to each coupe in an area not to be cut.

Soil Moisture Bores.

To allow measurement of soil moisture in the unsaturated zone, neutron probe access bores have been established at the rate of six per coupe and two in each control area. They are sited in pairs a few metres apart on upper slope, middle slope and valley floor situations. The control pair is sited on one of these situations.

Results.

As this project has only been running for approximately a year, it has naturally not yet proceeded into the logging or regeneration phases, but monitoring and analysis of the pre-cutting state is being carried out and has already yielded the following data:

Groundwater Tables.

TABLE 1

FLUCTUATIONS IN GROUND WATER TABLES
May 1975 to May 1976

Coupe	Fluctuation of water[2] level (metres)		No. of[2] bores with no water	No. of[2] flowing bores
	Mean	Range		
Crowea	2.17	0.10 - 5.50	2	1
Poole	3.42	1.00 - 4.50	2	0
Iffley	1.58[1]	1.99 - 11.60	1	2
Lewin	1.37	0.45 - 4.50	0	2
Mooralup	0.59	0.45 - 0.73	10	0

Notes: [1]Mean excluding one aberrant reading of 11.60 metres.

[2]The two control bores are included.

Variation between bores within a coupe was large. Little can be deduced from the between coupe means at this stage. Trends may become clearer after a further year's measurement.

Groundwater Salinities.

Thorough analysis of the data has not been considered worthwhile at this stage. Means and ranges of the levels of total dissolved solids for each coupe are shown in Table 2.

TABLE 2

SALT CONTENT OF GROUND WATER TABLE
May 1975 to April 1976

Coupe	No. of bores contributing[1]	Total Dissolved Solids mg/ℓ	
		Mean	Range
Crowea	9	339	127 - 760
Poole	10	712	296 - 2332
Iffley	11	762	285 - 1583
Lewin	11	509	148-- 1280
Mooralup	1	9237	-

Note: [1]The two control bores are included.

Salt in Soil Profile.

The analysis of salt content of the cores from groundwater bores was used to estimate total salt loads in the soil profile. Table 3 lists these estimates.

The coupes can be divided into two groups based on mean salt loads in the soil profile. Crowea, Poole and Lewin exhibit relatively light loads of around 10 kg/m^2 or less. Iffley and Mooralup both exceed 30 kg/m^2.

Within a coupe the salt load varied considerably from bore to bore and only one coupe, Crowea, exhibited uniformly low salt values.

Soil Moisture.

A relative estimate of soil moisture was made by comparing the count in the shield of the neutron probe with that at the measurement point in the access tube. Measurements were taken at 40 cm intervals to a depth of 6 metres.

Data collected to date have shown the wetting of the soil profile is fairly uniform to 6 metres depth in all coupes.

PROJECT 2: Paired Catchment Study.

Project Description.

Project 2 is designed to monitor both surface and underground water on a series of paired catchments, one of which would be cut over and the other remain forested as a control (Fig. 3).

After a period of calibration (4 to 5 years), one catchment of each pair is to be cut over and regenerated in the manner used by the wood chip industry.

The monitoring of the catchments is to continue until they return to the regenerated state.

A comparison of the cut over catchment hydrology to that of its uncut pair will show any effect due to the wood chip industry, and by gaining an understanding of the water and salt balances over a range of conditions, it should be possible to predict any likely changes in the hydrology of the area due to the wood chip industry.

Study Areas.

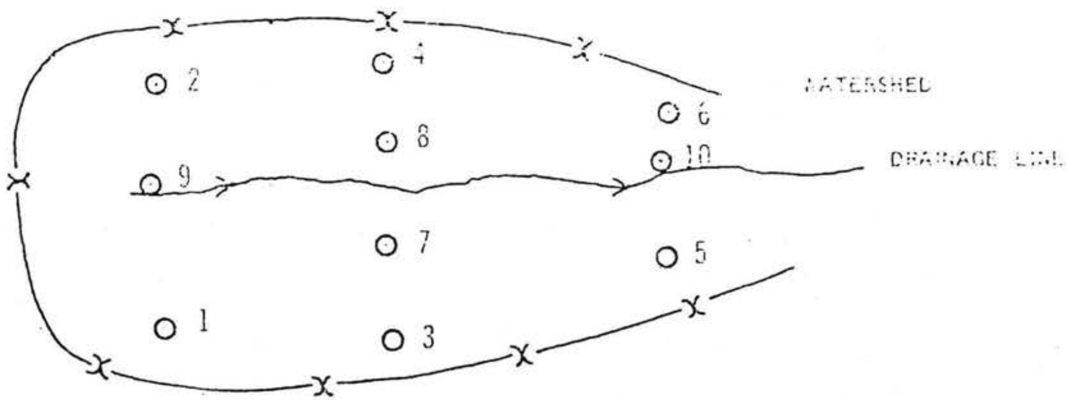
In the Wood Chip License Area, the jarrah-marri vegetation community is represented by two pairs of catchments, one in the low rainfall zone (900 mm - Warrup Block) and one in the medium-high rainfall zone (1150 mm - Lewin Block). The karri-marri forest is represented by a set of three catchments in the med/high rainfall zone (1150 to 1250 mm - Sutton Block).

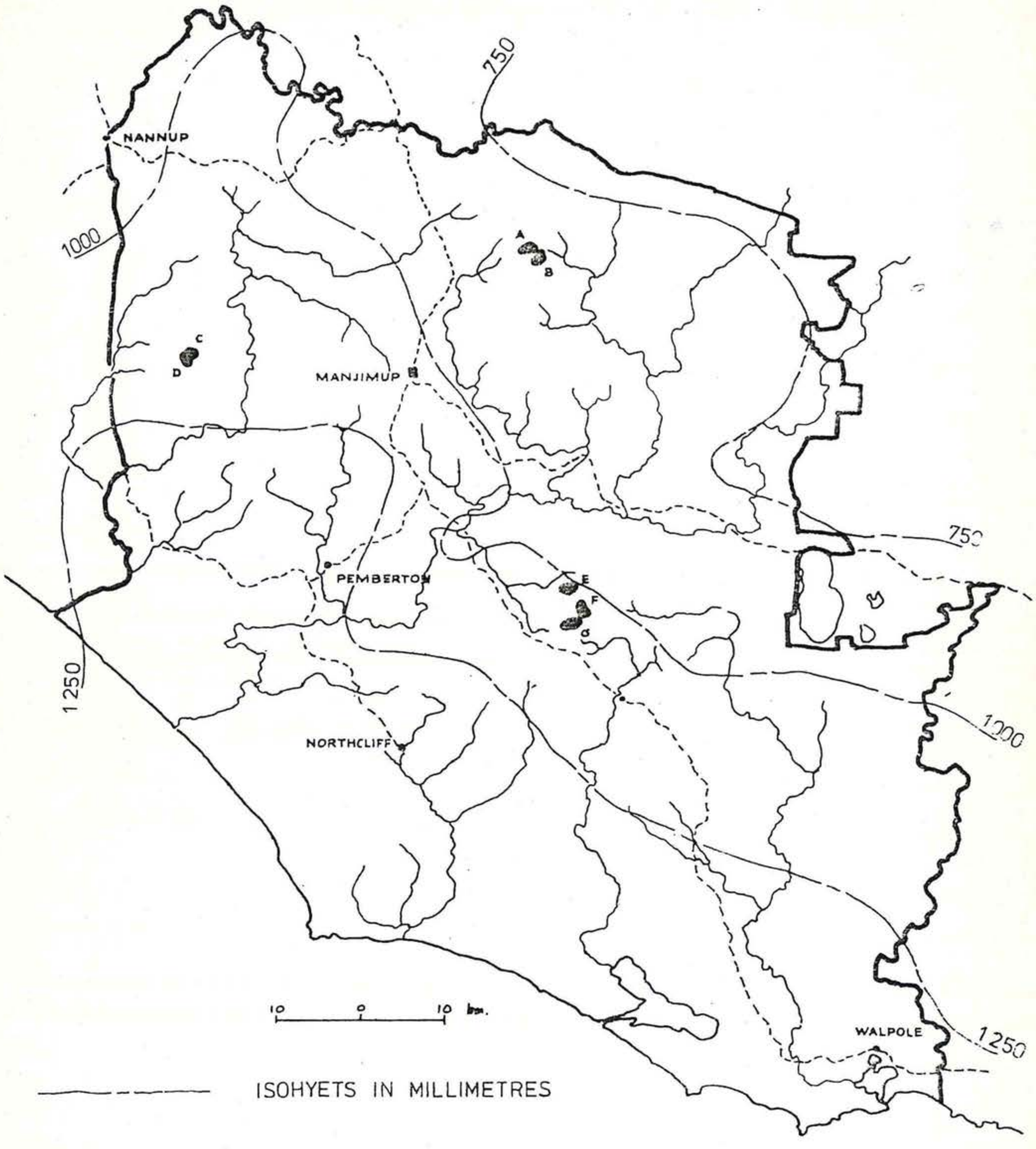
TABLE 3

SALT STORED IN THE SOIL PROFILE (kg/m^2)

Coupe	Bore No. 1	2	3	4	5	6	7	8	9	10	Mean
Crowea	5.4	3.5	1.3	7.8	4.1	8.6	8.2	2.1	2.8	11.3	5.5
Poole	N.A.	2.3	2.4	17.2	3.9	16.2	7.0	2.8	3.4	6.5	6.8
Iffley	54.2	53.1	35.3	18.0	38.4	55.7	2.9	10.0	26.8	14.6	30.9
Lewin	1.7	10.7	11.3	1.5	2.2	21.0	6.7	20.0	7.3	30.0	11.2
Mooralup	42.3	16.8	42.6	62.9	34.7	40.4	54.7	17.7	7.3	12.6	33.2

LOCATION OF BORE NUMBERS





LOCATION OF RESEARCH CATCHMENTS PROJECT 2

FIG 3

The Warrup Block pair (Fig. 4) are moderately dissected with laterite divides and podzolic soils on the valley slopes. The vegetation is typical low rainfall scrubby jarrah.

The Lewin Block pair (catchments C and D - Fig. 5) are more deeply dissected with laterites on the divides, podzols on the slopes and reddish loams in the valleys. The higher rainfall is reflected in the more luxuriant vegetation of mixed jarrah/marri and some karri in valleys.

The Sutton Block triple (catchments E, F and G - Fig. 6) represent the range of soils and vegetation types observed in repeated patterns across the whole transect of the karri/marri forest from the high to the medium rainfall zones. Catchment E is moderately incised with laterite divides, podzolic soils on the slopes and loams in the main valley, marri and karri dominate the vegetation with only a small area of jarrah/marri on the southern divide. Catchment F has a rather flat gradient and swampy flat uplands with grey sandy soils. Laterite is confined to the southern edge. Jarrah is dominant along the divides with karri on the north facing slopes and marri on the south facing ones. Catchment G has a moderate gradient. Jarrah dominates the lateritic headwater divides, and marri-karri covers the podzolic soils in the valley and on the slopes.

After investigation it was thought that this 'set' of catchments in the 1150-1250 mm rainfall zone gave a better overall representation of the karri/marri forest than two pairs situated over a wider rainfall range would have done. Ultimately two of these catchments will be cut over and the other remain uncleared as a control.

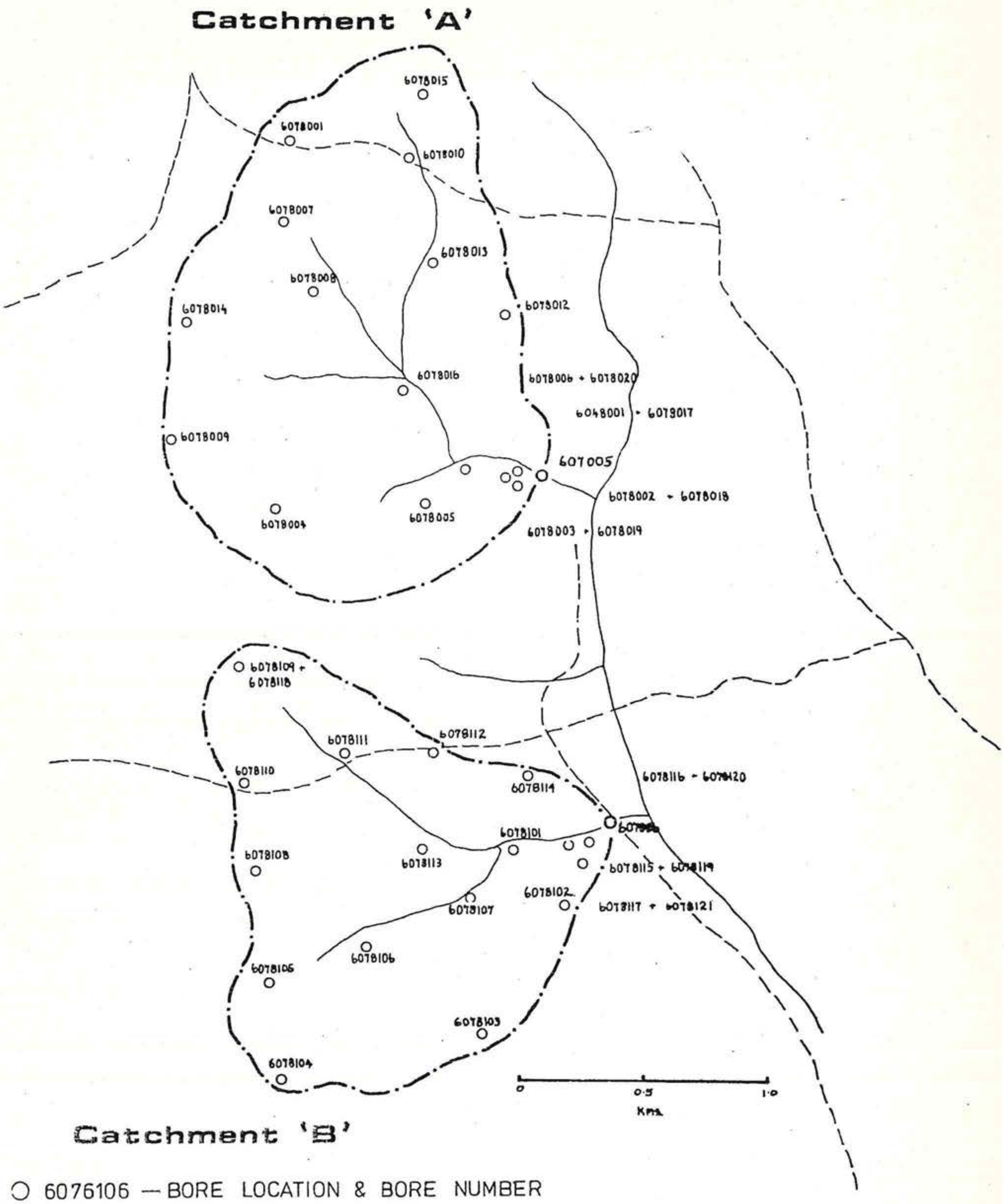
Surface Water

The surface water monitoring comprises measurement of the quantity and quality of rainfall and streamflow. The instrumentation for measuring the rainfall and streamflow is basically the same for all of the catchments.

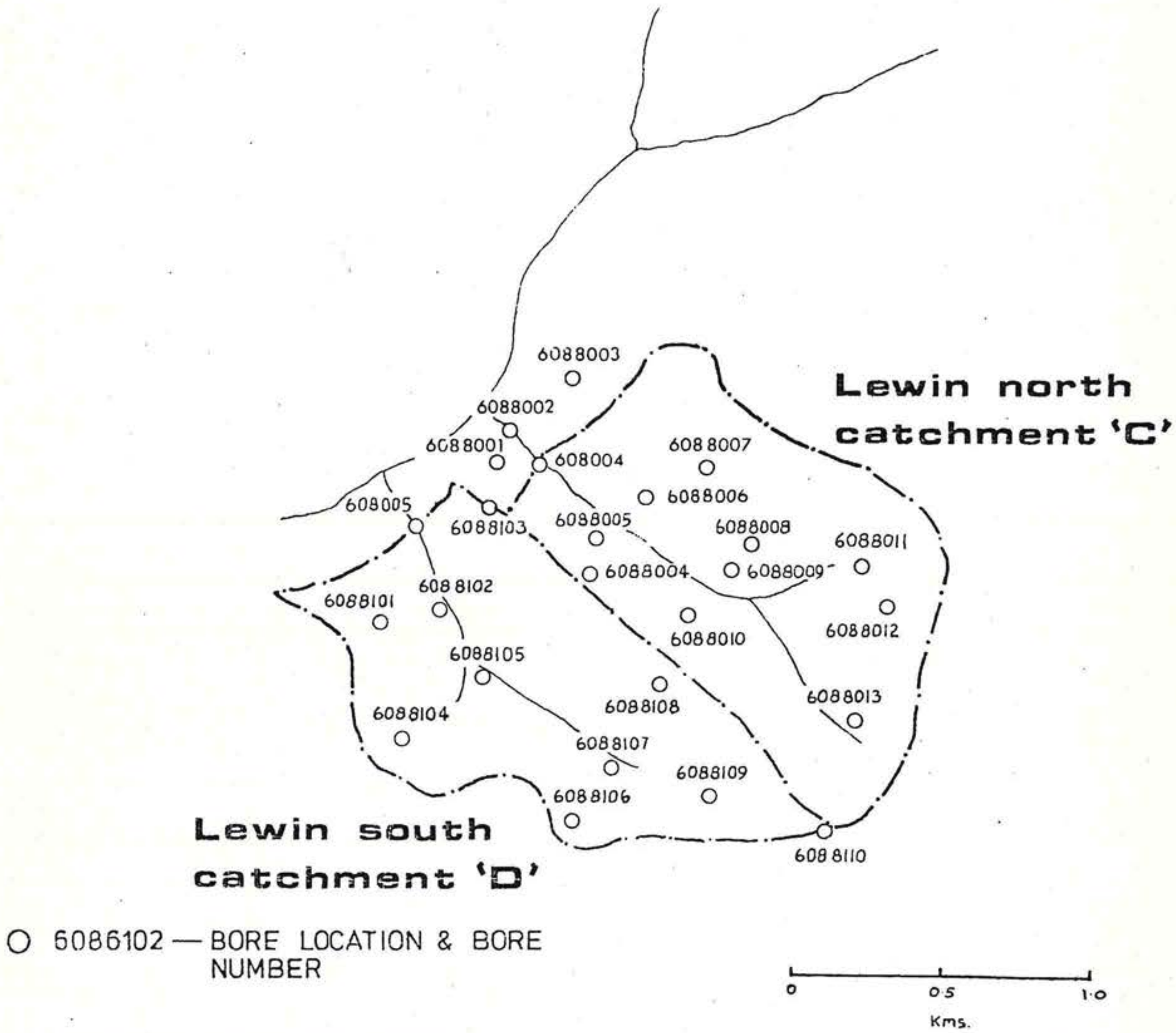
At the discharge section of each catchment a V-notch weir with a floatwell has been constructed and equipped with a Leupold and Stevens A35 graphical recorded which continually records stage height. A pumping sampler collects samples from the stilling basin of the gauging weir at 0900 hours each day. These samples are analysed for T.D.S., NaCl and turbidity. The amount of sediment deposited in the stilling basins is measured at the end of each winter and the stilling basin emptied.

Rainfall is measured by a Leupold and Stevens Q.A.C. pluviometer located at the top of each catchment and a tilting bucket pluviometer adjacent to each gauging station recording onto the A35 recorder.

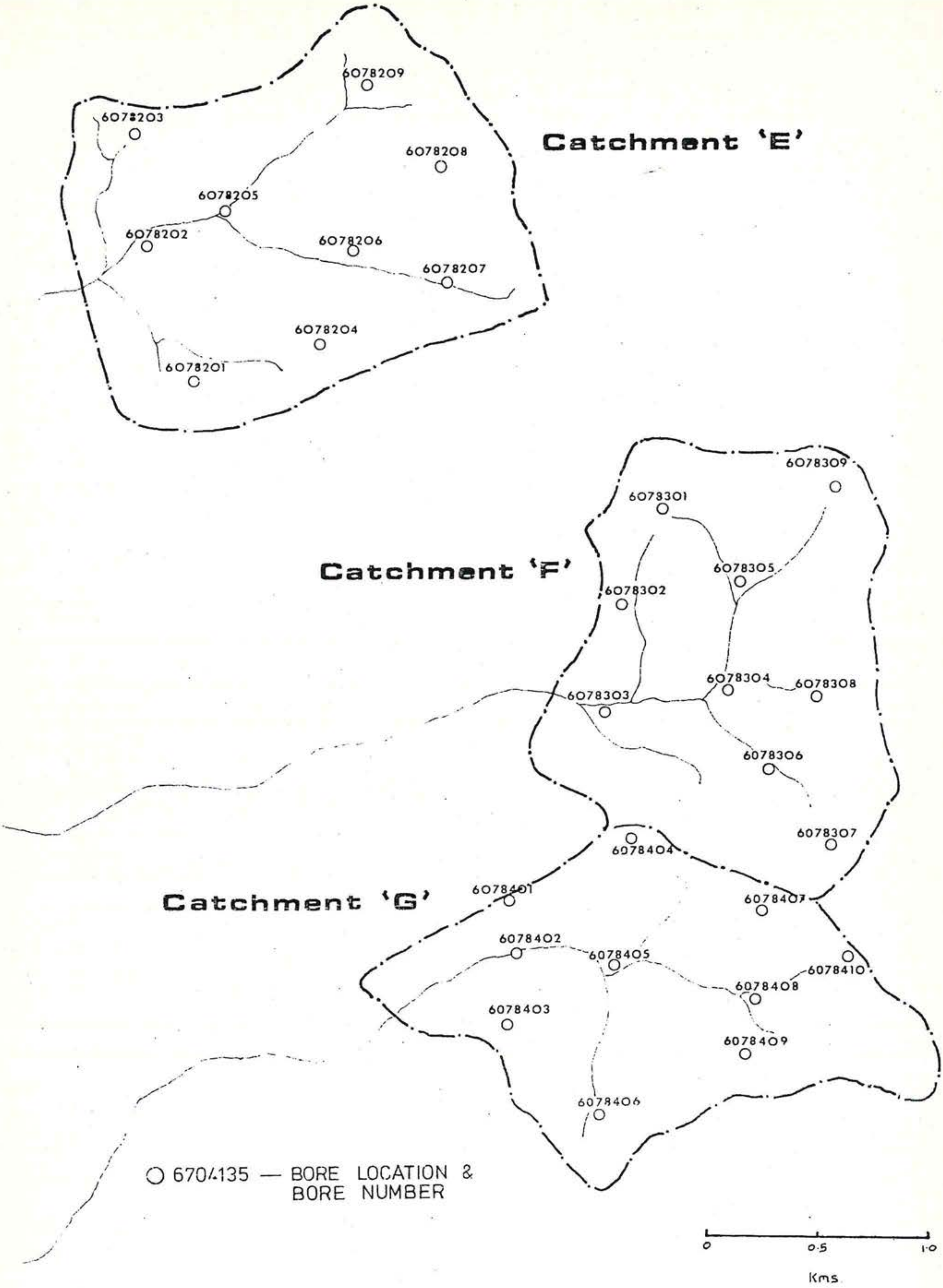
In the Warrup Block, near Manjimup, a climatological station instrumented to measure rainfall, evaporation, wind run, solar radiation and temperature onto a Rimco digital event recorder, has been established.



WARRUP BLOCK
CATCHMENTS A & B
FIG 4



LEWIN BLOCK
CATCHMENTS C & D
FIG 5



SUTTON BLOCK
CATCHMENTS E, F & G
FIG 6

Ground Water

As indicated on Figs. 4, 5 and 6, the groundwater system is monitored by 9 to 15 bores distributed uniformly throughout each catchment plus in some cases, 3 bores located at the discharge section of the catchments to assess the groundwater flow beneath the gauging station. On Warrup catchments A and B additional boreholes have been drilled alongside the 3 bores at the discharge section to determine whether flow within the bedrock is significant, but these have not yet been tested.

Seismic surveys have been carried out by Mines Department to determine the profile of the bedrock across the discharge section of each catchment and this technique is proving successful.

As for Project 4 soil cores taken during the course of drilling the groundwater bores are analysed for salt content to give an indication of the salt stored in the soil profile.

Results

Monitoring of both surface and groundwater on these catchments is now being carried out, but as this is a long term project final results are not expected for many years.

However for information salt storage values for a number of bores where the cores have already been analysed are shown in Tables 4 and 5. Salt storages are shown for each 2.5 metre interval as well as the total depth of the bore.

The data is presented in this way to give some idea of the vertical distribution of the salt and a more meaningful comparison between bores with differing depths and bores which may not have reached bedrock.

TABLE 4

SALT STORED IN SOIL PROFILES - CATCHMENTS D and E

Depth Interval (m) Bore No.	Salt Storage kg/m^2 0-2.5	2.5-5.0	5.0-7.5	7.5-10.0	10.0-12.5	12.5-15.0	15.0-17.5	17.5-20.0	20.0-21.5	Total	Depth of Last Sample (m)
Catchment D											
6088101	0.9	1.6	5.6	12.5	13.0	11.7	0.2			45.5	15.09
02	1.7	1.6	0.3	0.3	0.3	0.2				4.4	14.36
03	1.4	2.4	4.5	5.4	2.4					16.1	11.25
04	0.1	0.5	0.8	0.8	0.5					2.7	11.52
05	1.0	1.0	0.7	0.4						3.1	9.18
06	0.8	5.8	1.6	0.5	0.2					8.9	11.30
07	0.5	0.5	0.4	0.4	0.1					1.9	11.01
08	0.2	3.7	5.1	4.3	0.9	0.5	0.5	0.5	0.1	15.8	20.53
09	0.6	1.6	1.7							3.9	7.11
10	0.2	0.2								0.4	4.78
Catchment E											
6078201	2.1	7.4	3.4	2.0	1.1	0.6	0.4			17.0	17.24
02	8.9	7.5	1.1	0.7	0.5	0.4	0.4	0.4	0.1	20.0	21.22
03	0.7	1.2	1.3	0.5						3.7	9.51
04	0.2	0.2	0.4	0.8	0.6	0.5				2.7	14.03
05	6.0	7.5	1.4	0.9	0.9					16.7	11.78
06	3.5	5.4	1.3	0.6	0.6	0.6	0.5	0.3		12.8	19.09
07	0.4	2.9	7.7	2.2	0.5	0.4				14.1	15.35
08	0.2	0.7	1.6	1.9	3.1	4.0	1.1			12.6	16.16
09	3.4	5.3	4.0	1.5	0.6					14.8	11.85

TABLE 5

SALT STORED IN SOIL PROFILE - CATCHMENTS F and G

Depth Interval (m) / Bore No.	Salt Storage kg/m^2										Depth of Last Sample (m)
	0-2.5	2.5-5.0	5.0-7.5	7.5-10.0	10.0-12.5	12.5-15.0	15.0-17.5	17.5-20.0	20.0-21.5	Total	
Catchment F											
6078301	3.6	1.1	0.5	0.2						5.4	9.61
02	0.4	2.0	4.4	2.8	2.6	1.0	0.8	0.5		14.5	20.21
03	1.0	5.8	3.1	0.6	0.3					10.8	12.41
04	0.9	3.5	0.9	0.2						5.5	8.89
05	2.0	5.0	1.7	1.1						9.8	10.08
07	1.0	6.4	5.5	0.8	0.3	0.2				14.2	14.22
08	0.7	2.0	2.5	2.9	0.8	0.3				9.2	14.49
09	0.3	3.0	4.4	2.7	1.3	1.0	0.8	0.8	0.1	14.4	20.28
Catchment G											
6078401	0.6	4.9	2.7							8.2	6.07
02	7.7	4.1	1.6	1.4	1.2					16.0	12.23
03	1.1	9.2	8.3	2.6						21.2	8.88
04	0.7	0.6	0.7	0.5	0.4	0.3	0.2			3.4	16.17
05	6.2	2.2	0.8							9.2	7.28
06	1.2	5.1	1.5							7.8	5.5
07	0.3	1.1	1.7	2.6	4.4	2.7				12.8	10.41
08	0.4	2.3	1.1	0.7	0.1					4.6	
09	0.4	0.5	0.4	0.5	0.5	0.4				2.7	14.97
10	3.3	2.7	0.5	0.2						6.7	10.39

PROJECT 3: Monitoring at Stream Gauging Stations.

Project Description.

Project 3 is designed to monitor the runoff from the area over which the wood chip industry is to operate so that if there are any significant changes in the quality of flow in the major rivers, resulting from this industry, these changes will be detected.

Automatic pumping samplers were installed at nine existing river gauging stations in the Wood Chip License Area (shown on Fig. 7) which collectively measure runoff from some 80% of the area to be cut over in the first 15 years of operation.

A daily water sample is collected by the pumping sampler at each station. These samples are collected every four to six weeks and to date have been analysed for NaCl, conductivity and sediment. Turbidity and colour measurements will be added in the near future.

At each visit a sediment discharge measurement is to be taken with an additional pumped sample. It is hoped to develop a correlation between the sediment concentration in the sample collected by the pumping sampler and the concentration of sediment finer than 63 microns obtained from the comprehensive sediment discharge measurement.

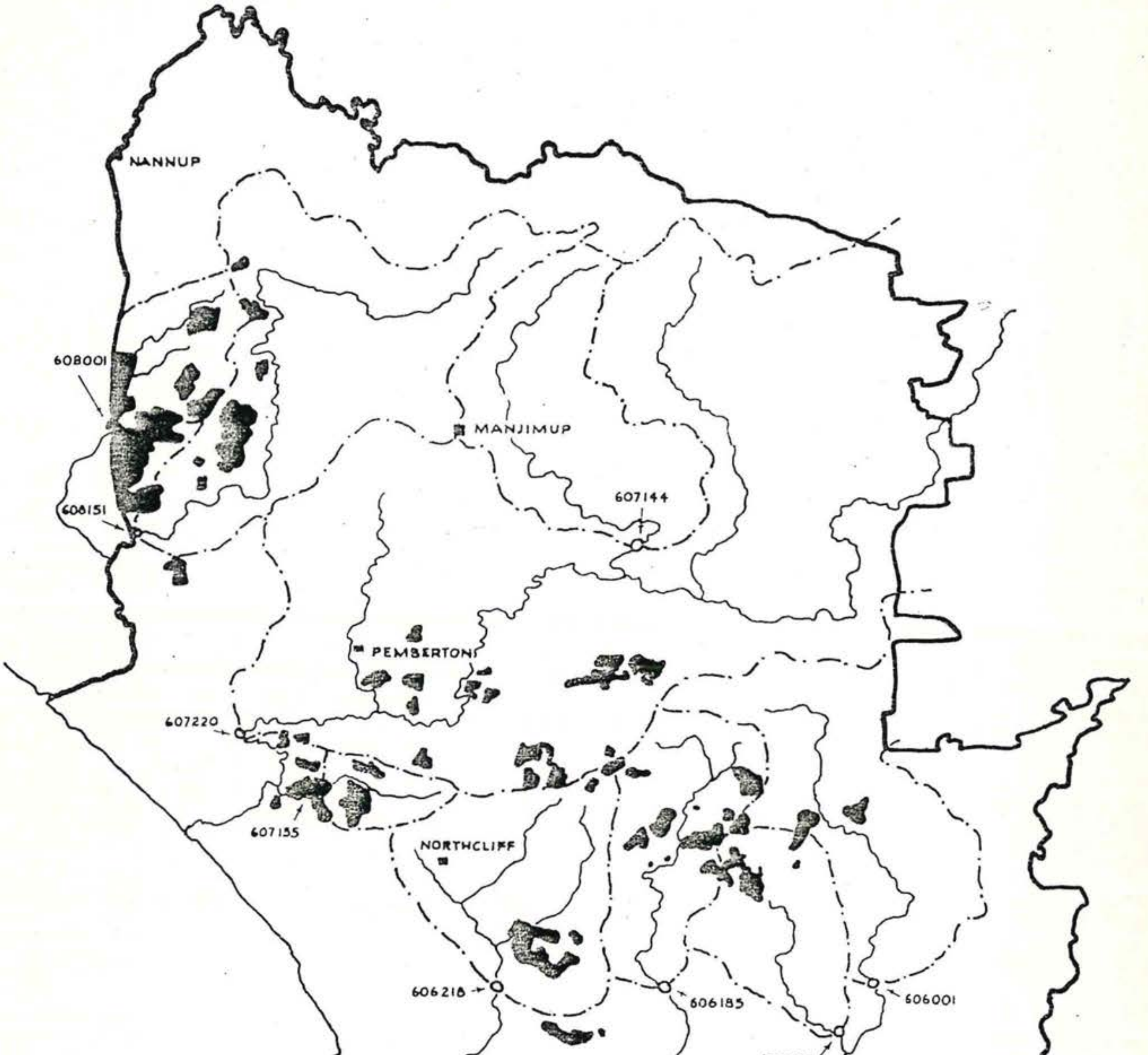
The gauging stations are all of good quality and produce an accurate and reliable flow record. The catchments have adequate rainfall networks.

Results

As a matter of routine daily water samples have been collected at these gauging stations since the latter part of 1975, but of the catchments monitored only the Warren has been subject to timber cutting for the wood chip industry at this stage.

It is too early to detect any effects due to the wood chip industry on the Warren catchment and because of the marked effect of appreciable clearing for agriculture on this catchment, changes due to the wood chip industry may be difficult to detect.

For interest runoff and water quality data based on earlier records up to 1974, collected at these gauging stations, are shown in Table 6 The water quality data shown in this table are derived from regular monthly sampling which is carried out at all river gauging stations in the south west of the State.



STREAMS MONITORED IN PROJECT 3

FIG 7

TABLE 6

NAME	STATION No	RECORD STARTS	PUMPED SAMPLES START	CATCHMENT AREA (km)²	AVERAGE RUNOFF		SALINITY - NaCl (mg/l)			PRIVATE LAND OR CLEARING
					($m^3 \times 10^3$)	mm	max	mean	min	
Deep River	606001	MAY 75	1-8-75	550	—	—	—	—	—	nil
Shannon River	606185	MAY 64	7-8-75	337	94 750	281	840	151	80	< 5%
Weld River	[illegible]	APR 64	4-8-75	258	60 000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Gardner River	606218	AUG 65	31-7-75	414	124 500	301	415	130	75	35%
Wilgarup River	607144	FEB 61	29-7-75	427	37 730	88	5 340	600	143	40%
Dombakup Brook	607155	MAY 61	31-7-75	115	47 430	413	680	[illegible]	52	[illegible]
Warren River	607220	MAY 66	5-8-75	3 870	348 800	90	3 950	520	150	—
Barlee Brook	608001	JUN 72	1-8-75	165	—	—	775	[illegible]	90	} [illegible]
Barlee Brook	608148	8-62 - 1/74	—	165	11 900	[illegible]	[illegible]	[illegible]	[illegible]	
Donnelly River	608151	JAN 61	4-8-75	805	156 900	195	300	[illegible]	[illegible]	[illegible]

ACKNOWLEDGEMENTS

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REFERENCE

W.A. Department of Agriculture (1974). The influence of land use on stream salinity in the Manjimup area, Western Australia. Technical Bulletin No. 27.

MODELLING OF HYDROLOGIC AND SALINITY PROCESSES IN A CATCHMENT

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Abstract

A soil-plant-atmosphere water flow model and a groundwater model for the study of catchment hydrology are outlined. These models, coupled together provide the basis for simulation of salt movement. The models are constructed on physical principles and require input values for the physical, chemical and biological properties of the catchment for model application. Initial simulation studies of vegetation clearing patterns on catchment water budgets suggest that parkland clearing of forest may minimize salinity hazards in the Collie area.

ABOUT MODELS

Models are common devices used by us all in one way or another to great advantage in our daily lives. Examples include cooking recipes, music scores, road maps and electric circuit diagrams. Each of these is an abstract representation of the real thing that can serve many purposes including problem solving. Each model is framed in its own particular "language" and we are conditioned or trained to think in terms of these languages as appropriate. Further, it can be seen that these models have a common structure being composed of <u>components</u> with particular <u>attributes</u> (properties, characteristics) and linkage <u>relationships</u> between components.

The use of models in gaining understanding of complex systems requires that there be a common "language" to describe the interactions between the various parts or subsystems. Mathematics has been used as this common language in many systems analysis studies. Most subsystem models in their original formulation can be re-expressed into a mathematically equivalent form thus providing a systematic tool for systems analysis. The development of a system model in mathematical terms requires careful formulation of coupling functions between the subsystem parts. Computer methods of handling mathematical relationships and for solving equations provide powerful techniques for investigation of complicated systems.

The complexity of ecological and environmental systems results from the large number of component parts. Each of these may have differing spatial distributions and temporal interactions often with non linear properties and differing lag time responses. The specific role of process models is the quantitative description of physical, chemical and biological phenomena based on established principles, hypotheses and theories about the processes and their interactions. The system model itself becomes a complex hypothesis since it can link subsystem hypotheses in series and parallel combinations.

Such process models are necessarily simplifications of the real world constructed with assumptions and approximations that must be borne in mind during the interpretation of simulation results. The very nature of the simplifications used in models requires the iterative study of results following sequential modification of model structure or input values. This procedure helps in gaining understanding of the relationships between model components and the sensitivity of the model output to change in component properties. A process modelling study of land use change and salinity in the Darling Range of south western Australia is being undertaken.

PROCESS MODELS FOR LAND USE - SALINITY STUDIES

The landscape of the Darling Range in south western Australia is considered in terms of two subsystems dealing with water flow and each of these couples with a salt transport model. The soil-plant-atmosphere water flow model takes rainfall input and calculates drainage recharge as input to a groundwater model (Fig. 1). The Terrestrial Ecosystem Hydrology Model (TEHM, Huff *et al.*, 1976) is being applied to assess the vegetation effects on soil water balances. The flux of water vapour from soil and vegetation is calculated in the TEHM model with the evapotranspiration equation developed by Monteith (1965). Each hour of the day, micrometeorological data and a surface resistance are used to calculate the vapour flux. The evaporating surface is assumed to be a plane that integrates the contributions from leaves and soil. A second equation, an empirical input function relates the resistance and water potential of the evaporating surface (analogous to the dependence of stomatal resistance on leaf xylem potential). A third equation describes the flux of liquid water to the evaporating surface from two soil layers which are occupied by roots. The flux of liquid water depends on hydraulic properties of the soil and the vegetation. Methods developed in the solution of electrical network equations are used to calculate the liquid flux. For any given soil water status, the rate of evaporation depends on the water potential of the evaporating surface. The evapotranspiration system is assumed to be at steady state, and a system of four equations and four unknowns is solved (Table 1).

This model provides relationships between the water inputs (precipitation), outputs (runoff, lateral flow, drainage, evaporation, transpiration) and storage changes (soil, interception). The mass balance of water requires that INPUT = OUTPUT + STORAGE CHANGE. A study of the model sensitivity to change in parameter values (Luxmoore *et al.*, 1976) showed that as the amount of vegetation (leaf area index) decreased there was a decrease in transpiration and increases in soil evaporation and deep drainage. Figure 2 shows these results for a July (summer) water budget of a Tennessee oak forest in terms of the output and storage components as a ratio of the precipitation input. The pattern of these results would apply to most soil-plant systems although the actual proportions may change considerably. Another study (Peck *et al.*, 1976) showed that change in soil texture from fine (scale factor 0.4) to coarse (scale factor 1.6) had almost no effect on the July water budget of a Tennessee oak forest (Fig. 3). This was a surprising result which may not be valid for all soil types

TABLE 1. Parameters and structure of TEHM, the soil-plant-atmosphere water flow model

<table>
<tr><th>Subsystem</th><th>Parameters</th><th colspan="2">Functional Equations</th></tr>
<tr><td>Atmosphere</td><td>Solar radiation;
Precipitation;
Dewpoint temperature;
Max. and min. air temp.;
Average wind speed;
Boundary layer resistances to heat and vapor flow.</td><td>Vapor flux from surface,
$F_v = f_1(R_x)$. (1)
Calculation uses combined energy balance - aerodynamic method.</td><td></td></tr>
<tr><td>Soil or Plant Surface</td><td>Resistance to vapor flow (R_x);
Surface water potential (ψ_x).</td><td>Surface water characteristic,
$R_x = f_2\ (\psi_x)$ (2)</td><td rowspan="3">Steady state:
$F_v = F_w$. (4)
Calculation assumes fluxes to and from evaporating surface are identical.</td></tr>
<tr><td>Plant</td><td>Resistances to liquid flow in roots and stems;
Root distribution in soil.</td><td rowspan="2">Liquid flux to evaporating surface,
$F_w = f_3\ (\psi_x)$ (3)
Calculation uses Darcy flow equations</td></tr>
<tr><td>Soil</td><td>Soil layer depths;
Soil water characteristic for each layer;
Hydraulic conductivity <u>v</u>. water content for each layer</td></tr>
</table>

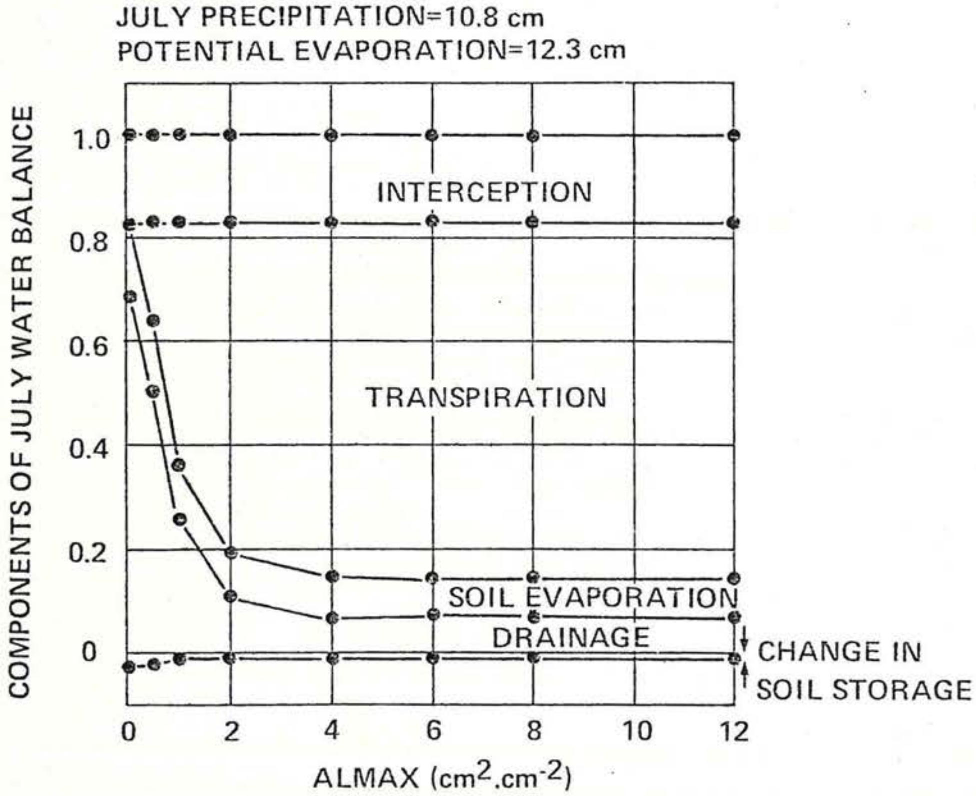

Fig. 2. Sensitivity of July (summer) water balance components to change in maximum leaf area index (ALMAX) of a Tennessee oak forest.

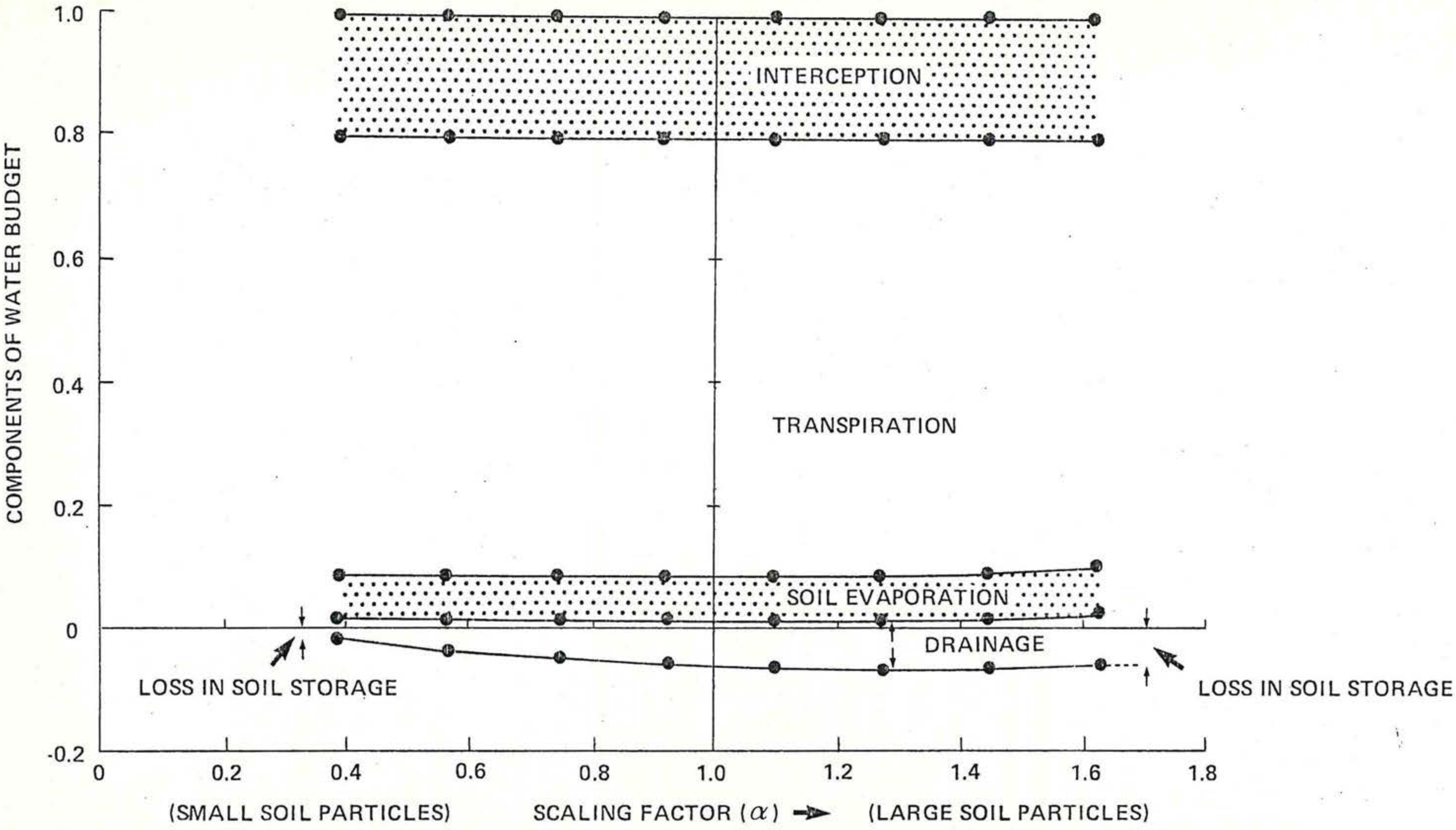

Fig. 3. Sensitivity of July (summer) water budget components to increase in soil particle size for a Tennessee podsolic soil with oak forest vegetation.

but it does illustrate that the soil can act as a very strong buffer in the water budget.

The transport of salt in the soil-plant system will be modelled with alternative algorithms of varying complexity. The simplest case assumes that there is a constant relationship between the amount of salt in soil solution and the amount of salt adsorbed on soil colloids. Experimental measurement of this distribution constant can be readily made for a particular experimental site. The model called SCEHM (Begovich and Jackson, 1975) couples with the TEHM code and the simulated water flow rates are used to estimate salt leaching with the soil drainage. At a later stage a more complicated soil chemistry model will provide for the effects of other soil solutes on the concentration of sodium and chloride ions in the soil solution. This part of the work is under development.

The mathematical model of the dynamics in the groundwater system is given by a two dimension flow equation having the following form

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y} \left(T_y \frac{\partial h}{\partial y}\right) + R\,(x,y,t)$$

where

S = specific yield of the aquifer (m^3/m^3)

h = hydraulic head of the groundwater (m)

t = time (hour)

x,y = two axis directions of the groundwater grid network (m)

T_x, T_y = transmissivity (m^2/hour)

$R(x,y,t)$ = groundwater recharge (+ values) or discharge (- values) ($m^3\ m^{-2}\ hour^{-1}$)

The term on the left hand side represents the time rate of change in groundwater storage. This term is numerically equal to the sum of the flow changes (gains or losses) in the x and y directions plus the groundwater recharge (or discharge). The latter term is calculated in the soil-plant water flow model as the deep drainage term. The application of the groundwater model to a catchment using a grid arrangement (Fig. 1) will allow the calculation of groundwater flow in the catchment and the watertable levels. In the grid cells in which watertables intersect with the soil surface, overland flow seepages will be simulated. Transpiration discharge ($R(x,y,t)$) from groundwater will occur in grid cells having the watertable within the root zone. The transmissivity and specific yield properties of groundwater systems can be derived from pump test data obtained from wells on the experimental catchments.

The transport of salt in groundwater by mass flow and diffusion-dispersion processes can be simulated with a two dimensional equation that couples with output from the groundwater flow model. The equation for salt transport is

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial \phi}{\partial x} - U_x \phi\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial \phi}{\partial y} - U_y \phi\right) + Q\ (x,y,t)$$

where

ϕ = salt concentration (kg/m^2)

D_x, D_y = diffusion-dispersion coefficient (m^2/hour)

U_x, U_y = simulated groundwater flow velocity ($m.^3\ m.^{-2}\ hour^{-1}$)

$Q\ (x,y,t)$ = addition of salt to the groundwater in drainage through unsaturated zone ($kg\ m.^{-2}\ hour^{-1}$)

The left hand side is the time rate of change in salt concentration and this is numerically equal to the sum of the diffusion-dispersion and convective changes in salt concentration plus the salt additions by drainage into the groundwater. In seepage areas predicted by the groundwater model salt will be transported as overland flow into streams. The diffusion-dispersion coefficients of salt in groundwater will be measured experimentally.

MODEL APPLICATION TO WIGHTS CATCHMENT, COLLIE

Wights Catchment near Collie is forested in an area with an average rainfall of about 1200 mm/year. The consequences of clearing the catchment for annual pasture were evaluated using the TEHM model. Conversion from forest to pasture in the simulation resulted in increases in both drainage and lateral flow and a decrease in evapotranspiration (Table 2). Winter (May-October) evapotranspiration was similar for pasture and forest however the forest evapotranspiration resulted in a much larger depletion of stored soil water during the summer than in the case of the annual pasture. This lower soil water status of forest land at the end of summer caused lower drainage and lateral flow rates during the early winter period (May-July) than for the pasture land.

An alternative form of clearing by the selective removal of trees and shrubs (parkland clearing) has also been estimated with the aid of results in Figure 2. The removal of half of the leaf area (leaf area index reduced from 3 to 1.5) by parkland clearing produced a significantly different set of simulated water budget components than strip cleared land with half of the forest removed (Table 2). There was greater evapotranspiration and less lateral flow and less drainage from the parkland than the strip cleared land. A parkland clearing with a 73% reduction in leaf area was estimated to have the same annual outflow (lateral flow + drainage) as land that was half cleared. These

TABLE 2. Simulated water balance components (cm/year) for four vegetation types on Wights Catchment, Collie.

Vegetation	Forest	Pasture	Strip* (50:50)	Parkland+
Summer Leaf Area Index	3	0	½ (3+0)	1.5
Winter Leaf Area Index	3	6	½ (3+6)	1.5
Evapotranspiration	87	46	66	77
Lateral flow	3	17	10	5
Drainage	38	68	53	46
Storage change	-2	-5	-3	-2

* Strip 50:50 calculated assuming that there is no interaction between the strips of forest and pasture.

+ values estimated with aid of figure 2 for a leaf area index of half the forest value.

differences are related to the effects of vegetation distribution on water budgets. The consequences of these clearing patterns on groundwater hydrology are currently under study.

Assuming that salts move in the soil with the soil water flux it is expected that the formation of seepages on cleared land would develop from the two components of the water outflow. Increase in lateral flow from temporarily perched water tables on top of the clay subsoil would give rise to seasonal seeps of low salinity water. The increase in drainage would cause a rise in the deep aquifer and the appearance of high salinity seepages. Implementation of the groundwater hydrology and salinity models will provide quantitative simulations of seepage dynamics.

DISCUSSION

There are several advantages and several problems with the systems analysis approach (Table 3) however if the majority of the problems can be alleviated the method is a powerful tool for systems study. Cases where the systems approach will not be helpful include ill defined systems. The example application was made to a well defined system and the results need to be evaluated in terms of the assumptions and approximations used in the models. TEHM code is currently limited to allowing roots in only the upper two soil layers (2 m soil in this case) however jarrah roots are known to penetrate to 15 m or more (Kimber, 1974). Thus the evapotranspiration values simulated could well be lower limit values and higher transpiration rates may actually occur in the field. This limitation of the model causes the conclusions made from the simulation results (Table 2) to be conservative. If a more realistic root sub-model was used, the evapotranspiration difference between forest and pasture would even be larger than the present result and thus the conclusions drawn would still hold.

The calculation of the strip clearing data (Table 2) assumed that there was no interaction between the pasture and forest areas. However, additional drainage and lateral flow from upslope cleared land may be absorbed by roots in downslope forest land. It is difficult to assess how effective downslope forest could be in transpiration of the additional water. In situations where this process was effective there may not be any hydrologic advantage of parkland clearing over strip clearing.

The example application of the process models has suggested that parkland clearing could minimise salinity hazard. It is clear that this forecast from simulation methods may be erroneous, nevertheless the method seems worthy of careful evaluation in field experiments. The parkland clearing may be a convenient intermediate stage to full clearing of the land. The suggestion being that some salt seeps may develop with parkland clearing but these would be less extensive than under full clearing. As the forest trees die out (assuming no regeneration in parkland pastures) there will be increases in the groundwater recharge and presumably more seepage. However over the period of 20 to 50 years this "controlled" release of salt may be less of a community hazard in terms of downstream water quality than the

TABLE 3. Some advantages and problems with systems analysis research.

Advantages	Problems
1. Gives quantitative results for a complex system.	1. Simplification of real world approximations and assumptions are required.
2. Helps to identify the relative importance of components in the system.	2. Not all factors are included. Results may be misleading.
3. A range of options can be examined case by case.	3. Usually requires some real world measurements as input (empiricisms).
4. Can examine a complex system without necessarily knowing everything about it.	4. Can be misused by not evaluating limitations of the approximations and assumptions.
5. Can choose the level of resolution or refinement suitable in the system study.	
6. Can be used to develop hypotheses and design experiments for further study of the system.	

TABLE 4. Catchment studies being undertaken with experimental and modelling methods.

Catchment	Native Vegetation	Rainfall (mm/year)	Land Use
1. <u>Collie</u>			
Lemon	Jarrah/Marri	850	agriculture
Wights	Jarrah/Marri	1200	agriculture
2. <u>Dwellingup</u>			
Del Park	Jarrah/Marri	1250	bauxite mining
3. <u>Manjimup-Pemberton</u>			
Mooralup	Jarrah/Marri	860	extensive logging
Crowea	Karri	1400	woodchipping

"pulse" release of salt when forest is cleared for agriculture. Longer term simulation studies will be conducted to evaluate these hypotheses.

The application of process models to the study of other land use changes (e.g. bauxite mining and rehabilitation, dieback and revegetation, woodchipping and reforestation) is also being undertaken. Data sets are being assembled for several catchments in which these land uses will be evaluated (Table 4) both in simulation and field experiment. Process modelling is most fruitful when it can be conducted in conjunction with field research. Both modelling and experimental methods are complementary and each method can be used as a check on the other.

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RESEARCH INTO LAND USE PLANNING

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Abstract

A quadratic programming model (TOPAZ) has been adapted to investigate optimum land use plans for the Murray catchment in Western Australia. The model, the objectives, the approach used, the problems and the possible benefits of the study are discussed. A comment is made as to the likely role of models in the planning process.

INTRODUCTION

Timber, water, recreation, agriculture or mining? Which of these or several other uses should take priority? Which forms of land use are best in the short and long term interests of this State? Where should each activity be located? Are some activities compatible?

In the northern jarrah forest in Western Australia (bounded by the Helena and Wellington catchments), competing land uses are vying for preference. Because of the value of this resource and its proximity to Perth and other centres of population, a number of people will be affected by land use decisions made here.

The resources of the area provide both wood and agricultural products, minerals (bauxite, gravel, coal, blue metal) and various recreational and conservational values. Of paramount importance is its use as a catchment for domestic and industrial water supply and for irrigation. The bulk is dedicated as State Forest and managed by the Forests Department of Western Australia. However, resource utilisation involves other Government departments, private companies and the individual landowners.

THE STUDY AREA

The Murray River is the largest in the region. Its catchment is located some 100 km south of Perth, has an area of 681,200 ha (upstream of Hughes bridge) and extends eastwards well into the agricultural belt. Precipitation varies from 1,300 to 425 mm per annum. Some 55 per cent of the catchment has already been cleared, causing water quality problems (the present weighted average is 1,000 mgl^{-1} total dissolved solids), and clearing is still continuing.

Collins (1974) calculated that the two major tributaries (the Hotham and Williams Rivers) contribute 44 and 22 per cent of the total flow. Their weighted average is 2,300 and 2,200 mgl^{-1} (t.d.s.) respectively. The western, forested portion covers about 20 per cent of the area and contributes about one-third of the flow. Values from streams in this zone are currently low (usually less than 500 mgl^{-1} (t.d.s.)). The average flow for the Murray (Hughes bridge, 30 year record) is $327 \times 10^6 m^3$, with a distinct seasonal influence and marked differences between years.

It is likely that this stream could be dammed for Metropolitan water supplies by the late 1980's (Hillman, 1971). Data indicate that a single major reservoir near Hughes bridge could provide an annual yield of about $250 \times 10^6 m^3$, with an average water quality of about 1,500 mgl^{-1} (t.d.s.). As a comparison, the total capacity of existing metropolitan dams is $493.4 \times 10^6 m^3$ and the annual metropolitan consumption (1974-1975) was $181.2 \times 10^6 m^3$ (MWSSDB, 1975).

The current upper limit for Metropolitan Water Supply is 500 mgl^{-1} (t.d.s.). The quality of the water from a dam on the Murray would therefore need to be improved. This could be achieved by

(a) mixing with less saline supplies,

(b) the construction of two dams and the bypassing of the saline flows around the lower dam,

(c) the construction of a number of smaller dams on the fresh, forested streams, or

(d) the rehabilitation of the saline agricultural catchments.

A dam on the Murray would drastically alter the current recreational and conservation values of the main valley. A dam could also affect other downstream values (e.g. the Peel Inlet). Within this catchment are some of the finest pole stands of jarrah, growing on high quality deposits of bauxite. Other parts (e.g. Dryandra State Forest) have well recognised conservation values.

These were some of the main reasons why this catchment was chosen for a research programme into catchment land use models.

THE STUDY TEAM

The core team comprises members from CSIRO's Divisions of Building Research and Land Resources Management, the University of W.A., the Department of Agriculture and the Forests Department. It includes Ecologists, Economists, Agricultural Scientists, Foresters, Programmers and Systems Analysts. Members of other Government departments and private companies have assisted as advisers in their specialist fields. Public opinion on some aspects has been obtained through surveys and questionnaires. Three bus tours of groups ranging from scientists to members of the public have been conducted within the catchment.

THE MODEL

A quadratic programming model, namely an Urban Planning model developed by Brotchie (1969), Brotchie *et al.* (1970) and Sharpe and Brotchie (1972), has been adapted to produce optimal land use plans for this catchment. This model, TOPAZ (Technique for the Optimal Placement of Activities into Zones) works through an extended linear programming algorithm. The model optimises land uses subject to various constraints (that a dam is or is not constructed, that viable areas are reserved for conservation purposes, that stream salinity is held below specified levels, that mining is held to the capacity of the processing plant etc.). In the output, the preferred land use activites are listed for each of the zones (both in a numerical and pictorial form). The total value of the land uses and the subtotals for each activity and zone are also shown.

THE METHODOLOGY

The land use activities considered relevant to the study were: indigenous and plantation forestry (eucalypt or pine), agriculture (beef grazing, orchards or wheat/sheep farming), bauxite mining (followed by protection or production forestry or agriculture), National Parks, Flora and Fauna Reserves and water storage; a total of eleven activities.

The benefits evaluated include the primary produce (timber, bauxite, fibre, cereal etc.), water yield, salt yield, recreational value and conservation. Economic evaluations included Cost/Benefit and Net Present Worth (Benefit-Cost) analysis at several discount rates. These data were calculated on a separate programme FINAN IV. Water and salt yields were expressed in $m^3\ ha^{-1}$ and $kg\ ha^{-1}$ respectively. Recreational values were obtained by estimating current visitor use, length of stay and growth in the recreational demand. Benefits were obtained by ascribing a dollar value to each visitor hour. Costs of recreational facilities were obtained from Departmental expenditure. Conservation values were usually calculated as the "opportunity cost" of the land use activity which had to be foregone.

The benefits were calculated for each zone where the activity was deemed feasible (e.g. wheat growing on western laterites and bauxite mining in dissected valleys were considered as non-feasible activities). Zones were defined primarily by land-form, rainfall and degree of clearing. The landform approach is based on the position and shape of the landscape units. These, in turn, reflect the distribution of soils and of vegetation. Although a single land-form may contain several soil and vegetation types, it is still suitable for a broad-scale classification. A landform map for the catchment has now been produced (McArthur, pers. comm.). Rainfall was selected because of its influence on land use, productivity, water and salt yields. Existing land use (as well as an indication of flexibility) was provided by the degree of clearing which has already occurred.

THE OUTPUT

It is not a function of this paper to examine outputs in any detail. This is being done in a separate report on the study. However, the types of runs which will be produced are listed, so as to provide an idea of the flexibility of the programme.

	No dam	One Dam	Two Dams
"Technical" Runs			
Various discount rates (2 to 14%)		X	
B/C against (B-C)		X	
Data variation			
Economic		X	
Recreation		X	
Water yield		X	
Salt yield		X	
"Policy" Runs			
No Land Use change	X		
No constraints at all	X	X	X
Minimum social disruption	X		
Continued agricultural clearing	X	X	
Salinity constraints			
500 mgl^{-1}		X	X
1000 mgl^{-1}		X	X
Conservation constraint	X	X	
Recreation constraint	X	X	

THE PROBLEMS

One of the important drawbacks so far has been the formulation of an appropriate economic philosophy. Some of the problems are:

* Different land use activities have different levels of infrastructure. This makes it difficult to find a common basis. The use of different economic criteria leads to different land uses being chosen.

* Land transactions are, in essence, transfers of resources and so have not been considered. Some (especially resumptions) have both real and social costs.

* It would seem logical to consider all projects over a similar time horizon. That used for the jarrah forest is 120 years. Who dares to forecast the future for that span of time?

* Other, more pragmatic problems (rates of inflation and discount, option value, consumer surplus, recreational value of a visitor day etc.) are common.

* Is optimisation a "real life" solution or should we look to a different objective (diversity, flexibility, resilience)?

As expected, a number of inadequacies in the data base soon become obvious.

* Physical parameters for water and salt yield need to be estimated for 10 land uses over 53 zones, but there were only 11 gauging stations in the catchment until recently. Most of the gauged catchments contain a range of land-forms/land use practices.

* Estimating biological input/outputs is difficult in those areas outside current experience, where no trials have been performed or where experimental work is in the early stages of development. In contrast, other aspects have been researched in considerable depth.

* Even where data is available, there is the problem of extrapolation from the micro to the macroscale.

* Although current costs can be evaluated fairly easily, the assessment of future prices is far more difficult. This becomes a lesser problem when one uses Benefit/Cost and high discount rates.

The next class could perhaps be described as the human element.

* The "bias" of the members in the study team.

* The inadequate allocation of time by both individuals and by organisations to the study. This is understandable when one considers that the project is run as part of already full programmes by the officers concerned, by the lack of assurance within the team that the project will lead to practical land use plans which will not conflict with their Department's objectives and by the ever present problem of allocation of rewards for effort expended in an inter-disciplinary study.

* Since the limitations of the data base are not concealed, there is always an opportunity for affected groups to question the validity of the conclusions, and express a refusal to be influenced by them. Yet their own decisions must in essence be based on similar evidence, but not necessarily revealed publicly.

* There is also dissatisfaction among the scientists at the "uncontrolled" nature of the experiment and the inadequate data base. Yet, while scientists remain silent, important decisions affecting social welfare may be made ....

* The "acceptability" of the various alternatives to Government, the public and the people who live in the catchment is not known. It seems obvious that the opportunity to comment and to provide input should be given to these, and to other groups.

Fourthly, there are the problems of scale and of boundaries.

* A dam on the Murray River would cut off the last major river which feeds into Peel Inlet (an important, coastal, tourist facility). What is the likely environmental effect of such a proposal? Who would dare to ignore the effects on Peel Inlet in a study of this kind?

* The conservation, water, bauxite, timber and agricultural benefits are not exclusive to this catchment. The study is obviously dependent on the availability of these products in other catchments, or perhaps even other States. No catchment is an island .... where should a study such as this end?

THE BENEFITS

After the preceding discussion, one may wonder if there are ANY benefits from such a study. Perhaps these could include:

* The mutual exchange of data, of techniques and of philosophies between various individuals and organisations.

* The cooperation between the various bodies with a vested interest in the area does not ensure, but may lead to, reasonable compromise rather than to direct confrontation between the various parties.

* The airing of "new" concepts - such as agroforestry (low density forestry so as to stabilise salt outflow from farmland). The redirection of research emphasis and of staff into newer, "more fruitful" lines.

* The need to ask pertinent questions on the "real" costs of water and of salt .... or the "real" benefits of recreation.

* By changing the weightings (or data) used, the view of different parties (developer, conservationist, miner, recreationalist, etc.) can be represented. Conflicts can then be explored by sensitivity analysis.

* We do not claim that the model provides either the "best" or an "infallible" solution. Rather, it is a means of examining the likely consequences of a particular decision or assumption. Used in this role, TOPAZ can be a most useful tool.

THE FUTURE

Having developed and tested the model, the main interests and purpose behind the initial study will have been satisfied. The model will then be available for use by existing Land Use agencies. Do the existing land users see any value in this approach? Are the techniques outlined likely to satisfy their planning needs? Are the solutions which have been nominated feasible .... or even sensible?

The data base for the model can be readily updated as better data is made available. A wide range of land use alternatives can then be produced for consideration. Assessment by Government departments, private companies, landowners and the public can then take place. This is likely to lead to an improved data base and the production of further alternatives. Finally, those with the greater merit will emerge for consideration. It is also possible that TOPAZ could be used in other areas where complex land use decisions need to be made (land use planning in the south-west, the sunklands, the chipwood licence area, the Wellington catchment, etc.).

One must stress that the formulation of an optimal set of activities is not a goal in itself. It is quite a different and difficult task to design legislation and implement the controls which will be necessary to achieve the desirable plan. Since many of the benefits do not accrue to either the land-owners or the land managers, a considerable degree of resistance is likely. Even if TOPAZ provides a better technical basis for Land Use decisions, legislative, social and political barriers will still occur. It could be argued that the "real cost" (if such a thing exists) may be the last thing that planners, politicians, Heads of Departments, Company Directors and ecologists, really want. Land use policies are largely the result of political decision. As such, they are based on political, not technical criteria. Perhaps these are some of the reasons why models such as TOPAZ have not been widely used in the past.

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