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PRE-PRINT of paper to be presented at the International Conference on "The Agricultural Industry and its Effects on Water Quality", Hamilton, New Zealand, 15-18 May, 1979 and later published by Pergamon Press in their "Progress in Water Technology" series.

AGRICULTURAL LAND USE AND ITS EFFECT ON CATCHMENT OUTPUT OF SALT AND WATER - EVIDENCE FROM SOUTHERN AUSTRALIA

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ABSTRACT

Agricultural development over the past 200 years in southern Australia has involved extensive clearing of the native, evergreen vegetation and its replacement with annual rain-fed crops and pastures. These introduced plants have a limited growing season, are comparatively shallow rooted and hence, in a Mediterranean climate, use less water. A consequence of this is the secondary salinisation of about 277,000 ha of previously productive land, and associated degradation of valuable water resources. These effects were first noted in the 1890's, and by 1924 it was hypothesised that increased recharge caused a rise in levels of saline underground water bringing salts to the soil surface particularly near water courses.

Studies initiated in the 1960's have shown that large quantities of soluble salts are stored in the deep weathering zones characteristic of southern Australia. Under forested conditions, surface and near surface waters are relatively fresh although deeper groundwaters may be highly saline. Data presented show that groundwaters rise as a consequence of clearing. This leads to the development of saline seeps, which, together with an increase in saline baseflow, results in increased salt export from catchments. Although there is usually a concomitant increase in run-off, this may not be sufficient to keep annual stream salinity below an acceptable level.

The pattern of changes in streamflow quality during the year is shown to provide an indicator of the contribution of saline baseflow to streams from small catchments. This may be useful in predicting the effect of clearing, or in indicating a decline in saline baseflow following re-afforestation.

KEYWORDS

Clearing, saline seeps, groundwater, recharge, water quality, streamflow, salt balance.

INTRODUCTION

The utilization of land resources for large-scale agricultural development is a relatively recent activity in Australia. In 1870 the area of cultivated land was about 1 million hectares, increasing to 43 million hectares by 1977 (Australian Bureau of Statistics, 1978), with about 85% being in the southern third of the continent. Development has involved the removal of much of the native vegetation of primarily evergreen perennial shrubs and trees, of which many have root systems extending well beyond 1 m depth (Grieve and Hellmuth, 1968; Kimber, 1974). In contrast the introduced crops and pastures are generally shallow rooted with 95% of roots in less than 1 m of soil (Ozanne, Asher and Kirton, 1965). Williamson (1973), in a study of water content in a deep sand, showed that the native vegetation of heath and sclerophyll scrub extracted a larger quantity of water from a greater depth (to 3 m) and for a longer period than was the case for an adjacent wheat crop.

Hydrologically, the change to agricultural land use results in increases in stream flow and recharge of groundwater, and the development of water-logged soils (Wood, 1924; Bettenay, Blackmore and Hingston, 1964; Boughton, 1970; Holmes, 1971). In parts of southern Australia the hydrologic changes are associated with increases in salinity of soil and surface water resources. Similar secondary salinity has affected the soils of about 800,000 ha of the northern Great Plains region of North America (Vander Pluym, 1978). Peck (1978) has proposed the expression "saline seep" for areas where groundwater movement to the soil surface has produced a salt-affected soil.

This paper reviews the evidence for salinisation of soils and streams in southern Australia, (Fig. 1) resulting from dryland agricultural development following European settlement. Data are presented to support the hypothesis that the post-clearing change in the ground water system is the major contributory factor in the development of saline seeps and increased stream salinity. Ongoing research in several small catchments is used to examine other related responses to clearing.

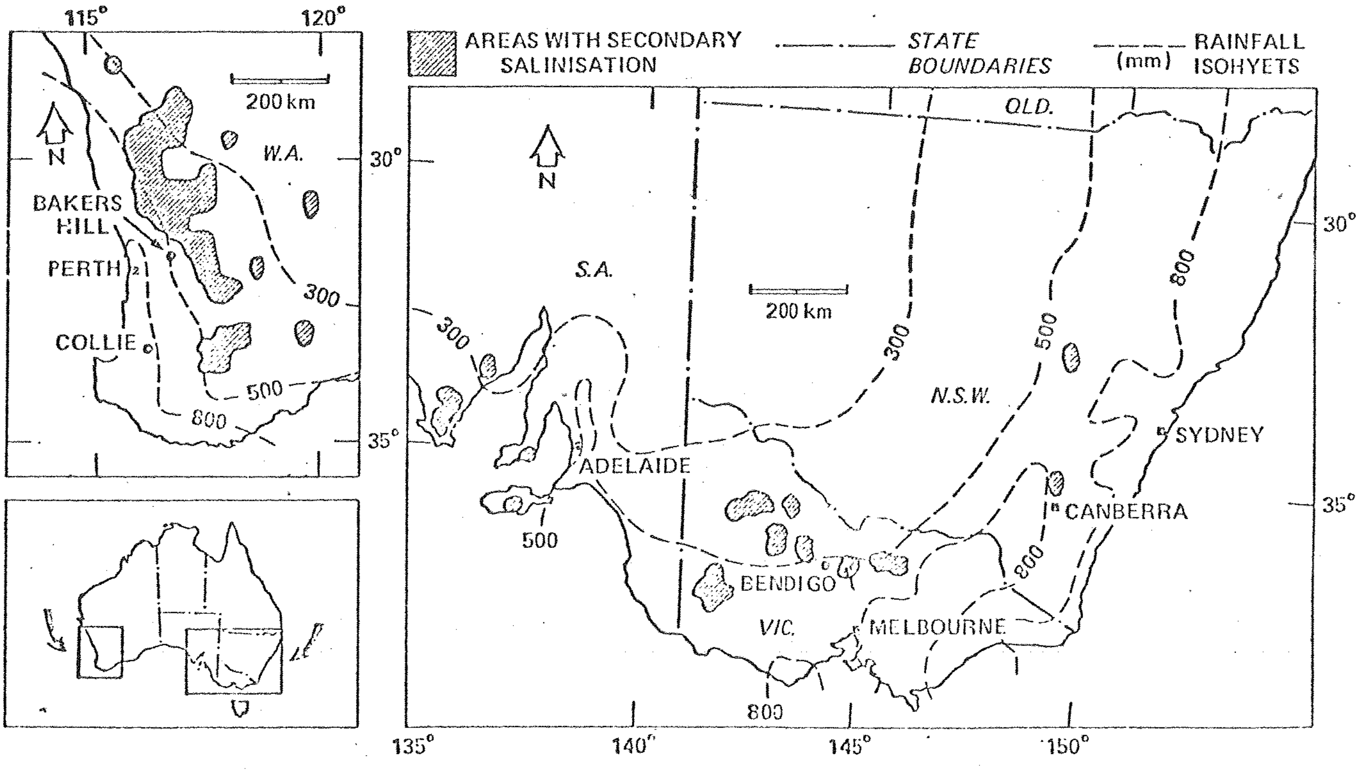

Fig. 1. Location in southern Australia of areas where secondary salinisation of soils exceeds 2% of the land used for non-irrigated agriculture (Sources: as for Table 1, also Northcote and Skene, 1972).

PHYSICAL ENVIRONMENT

Climate

Agriculture in southern Australia depends on winter and spring rainfall for the major crop and pasture production. In all but the eastern highlands, the climate is predominantly Mediterranean, with an excess of winter rainfall, followed by summer drought; median annual rainfall is generally less than 800 mm (see Fig. 1) with a low to moderate annual variability. Class A pan evaporation, as a measure of potential evaporation, is in the range 1600 to 2400 mm per year. Average annual temperature is in the range from 12 to 20^{o}C, with the average daily maximum for January in the range 24 to 35^{o}C and the average daily minimum in July being in the range 3 to 9^{o}C (Year Book of Australia, 1977).

Except for a more marked decline in runoff towards the inland areas, the patterns of annual runoff and rainfall are quite similar. Most streams and rivers are either strongly seasonal, or ephemeral in nature, and therefore storage reservoirs are essential for maintaining water supplies throughout the year.

Soils

Saline seeps which develop following land clearing for dry-land agriculture are frequently associated with duplex soils, either solodized solonetz and solodic soils, or lateritic podzolic soils, underlain by deep kaolinised pallid and weathering zones.

In Western Australia, saline seeps are also found in lower slope situations of extensive areas of yellow earths which have an indurated lateritic mottled zone at variable depth (Bettenay, 1964). Saline seeps occur in the alkaline sodic coarse- and medium-textured soils at the base of dunes in north western Victoria (Northcote and Skene, 1972), while areas of significant non-irrigated secondary salting in Victoria occur within a number of soil groups additional to those mentioned above including grey cracking clays, solonized brown soils and soloths (Stace and colleagues, 1968; Mitchell and colleagues, 1978).

The chloride ion dominates the anions, and sodium the cations, in the majority of saline Australian soils to the extent that sodium chloride comprises from 50 to 80% of the total soluble salts (Northcote and Skene, 1972). The criterion used for soil salinity is usually a visual one involving absence of vegetation and presence of salt efflorescence at the soil surface. In classifying soil as saline, Northcote and Skene (1972) used 0.1% to 0.2% NaCl for surface soil and 0.3% NaCl for sub-soil, but the paucity of chemical data has usually restricted the objective approach in surveys of salt encroachment.

ORIGIN OF SALTS

It is now well documented that rain carries with it quantities of salts which are largely of marine origin (Ericksson, 1952; Hutton and Leslie, 1958). The geographic variation of salt precipitation over Western Australia has recently been described by Hingston and Gailitis (1976) who show a general decrease of the annual mean chloride concentration in rainfall with distance from the coast. Aerosols produced from oceanic spray are carried inland, where, because of the high ratio of evapotranspiration to precipitation for native vegetation and the nature of the landscape, the salts are concentrated in both soil water and groundwater. The features of the landscape conducive to the retention of cyclic salts include the extremely low gradients (as low as 1:1500), the low hydraulic conductivity of the kaolinised soil zone (of order 10^{-2} m day^{-1} (Peck, 1976b)), the disrupted nature of the regional drainage, and the presence of a deep regolith (to 50 m) consisting largely of highly weathered saprolites of the country rocks (Bettenay and Mulcahy, 1972). Under these conditions the quantities of salts stored can be very large (Bettenay, Blackmore and Hingston, 1964; Dimmock, Bettenay and Mulcahy, 1974). The latter authors found that for an area receiving an annual rainfall of 600 mm in south Western Australia, mean storage of total soluble salts (TSS) was 10^6 kg ha^{-1}. The total amount of stored salt decreased with increasing average annual rainfall. At least 75% of this salt is stored in the unsaturated zone (C.D. Johnston, private communication). Where the deep kaolinised zone is absent, the storage of soluble salts in the landscape appears to be relatively small (Mulcahy, 1978), with a consequent absence of saline seeps.

Atmospheric accession is also the primary source for salt accumulated in soils and deep saline aquifers of the northern slopes and plains of Victoria (Downes, 1954; Mitchell and colleagues, 1978), and in deeply weathered profiles of the Eyre Peninsula, York Peninsula and Kangaroo Island in South Australia (Matheson, 1968) (see Fig. 1). The Riverine plains in north-western Victoria have aquifers developed from Tertiary limestones of marine origin which provide an additional source of salt for secondary salinity (Macumber, 1968). Relict salts, possibly of marine origin, and mineral constituents of weathering parent rock are considere sources of soluble salts for small, widely scattered saline seeps in the sub-humid Tablelands and Slopes of New South Wales (van Dijk, 1969; Hamilton and Lang, 1978). The importance of marine sediments as a source of stored salts should be gauged against the adequacy of the post-marine-transgression period for accumulating large quantities of salt in soils through atmospheric accession. For example, assuming that all precipitated salt was stored, and that there was no variation in an accession rate of 20 kg TSS ha^{-1} yr^{-1}, it would require 5 x 10^4 years to accumulate 10^6 kg TSS ha^{-1}.

SOIL AND WATER QUALITY CHANGES FOLLOWING EUROPEAN SETTLEMENT

The most recent estimates of the area of secondary salinity of non-irrigated soils in southern Australia are given in Table 1, and mapped in Fig. 1. The total area of 277,300 ha represents less than 2% of the land cleared for agriculture in any State. These data refer to obviously saline soils frequently devoid of vegetation There is no known estimate of the area of soils in which reduced yield is a consequence of salt encroachment. Both in Australia and in North America the area of saline seeps is continuing to increase (Peck, 1978).

In southern Australia, the first recorded observation of increased stream salinity following destruction of native vegetation, was made in the 1890's on the Yorke Peninsula in South Australia (Wood, 1924). In Western Australia, changes in water quality in small earth tanks constructed for railway water supplies was first noted by Bleazby (1917) where clearing of the catchments was used to increase water yield. Wood (1924) further associated agricultural development with increased salinity of rivers including the Hotham, Gordon, Arthur, Preston, Blackwood and Murray rivers in Western Australia. All were used for railway boiler water at the beginning of the century but eventually became unsuitable for both this purpose, and domestic and irrigation water supplies. Further evidence was provided by an increase in the salt concentration of the Mundaring reservoir near Perth, Western Australia, after trees in part of the catchment were ring-barked in 1903 to increase water yield (Kessell, 1920). The apparent success of a re-afforestation programme was confirmed by Weller (1926) who found that, from 1914 onwards, there was a dynamic balance between catchment salt input in the rainfall and salt flow into the Mundaring reservoir.

In the 490 mm to 1370 mm rainfall zone of south-west Australia, Peck and Hurle (1973) determined the salt flow:saltfall ratio in forested and farmed (>30% cleared) catchments whose areas ranged from 400 to 380,000 ha. For 8 forested catchments the ratio was in the range 1.1 to 1.6 indicating only a small excess in chloride ion export, and average stream chloride concentrations did not exceed 240 mg ℓ^{-1}. However, with ratios ranging from 3.1 to 21.0, it was reasoned that chloride ion was being removed from storage in the 7 farmed catchments examined. Streams from 5 of the farmed catchments had average chlorid concentrations of 1200 mg ℓ^{-1}. Given sufficient time, and no increase in clearin notable improvements in quality of streams draining farmland could be expected as equilibrium conditions were re-established. Peck and Hurle estimated equilibrium concentrations similar to the present acceptable levels of the forested catchments. However, characteristic times were from 200 to 400 years where the average rainfall was less than 1000 mm yr^{-1}.

TABLE 1 Estimated area in hectares of secondary salinity of non-irrigated soils in southern Australia

STATE	AREA ha
Western Australia[1]	167,000
South Australia[2]	14,000
Victoria[3]	85,000
New South Wales[4]	11,300
Tasmania	actual area unknown but negligible

Sources:
[1] Malcolm and Stoneman (1976)
[2] Matheson (1968)
[3] Mitchell and colleagues (1978)
[4] Hawkins, C. A., private communication, estimate only, no detailed survey done.

Clearing of land for agriculture over the last 80 years is considered the primary factor in the current situation where 40% of surface water resources in south-west Australia is sub-potable, having an average annual flow-weighted total salt content exceeding 500 mg ℓ^{-1} (Sadler and Field, 1976). In addition, salinity threatens the future of some current water supplies. The Great Southern Towns Water Supply and an irrigation district of 16,200 ha are dependent on water from the Wellington Dam which impounds the Collie River and its tributaries in south-west Australia (see Fig. 1). Since 1960, when the wall of the dam was raised to obtain a reservoir capacity of 185 x 10^6 m^3, there has been a gradual increase in the chloride content of the reservoir inflow (Fig. 2). The degradation of the inflow has been positively correlated to the increase in clearing of land for agriculture in the catchment (Loh and Hewer, 1977). The rate of increase of salinity has continued to increase despite a reduction in the rate of clearing. Although legislation in 1976 has severely restricted clearing in the catchment, a steady-state salt and water balance model (Peck, 1976a) used by Loh and Hewer indicates that average annual inflow salinity could rise to 1100 mg ℓ^{-1} TDS (about 580 mg ℓ^{-1} chloride). At the current rate of increase this peak would be achieved by about 1983.

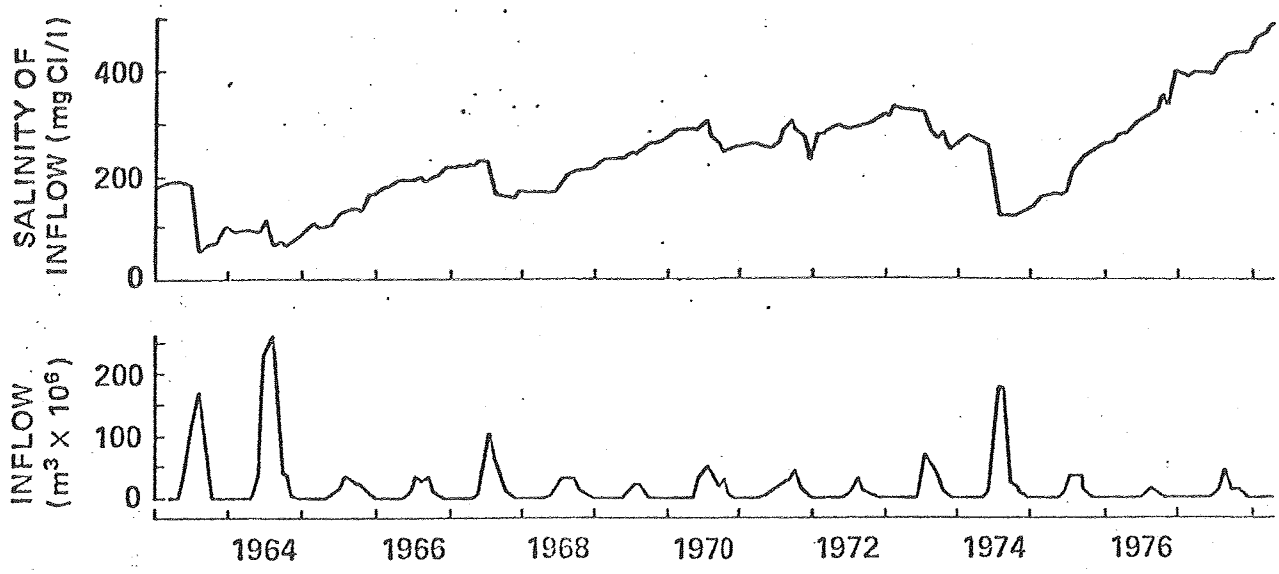

Fig. 2. Trend in average monthly chloride concentration of inflow to the Wellington Dam in Western Australia for 1963-1977, and associated total monthly streamflow. (Source: Public Works Department of Western Australia.)

A change in vegetation need not be the only means for generating conditions resulting in saline seep formation. In the northern slopes of Victoria, the use of contour banks to control a severe soil erosion problem, has led to the development of saline seeps, apparently through diverting harmful run-off to infiltration (J.J. Jenkin, private communication). In Western Australia, it was considered by Conacher (1975) that exceptionally high potentiometric heads in a deep saline aquifer beneath a salt seep may be a response to an interceptor bank system which diverted overland flow and throughflow into the aquifer.

HYPOTHESES FOR SALINE SEEP DEVELOPMENT

As an explanation for the development of saline seeps and increased stream salinity, Wood (1924) put forward the hypothesis that the removal of deep-rooted native vegetation increased recharge through old root channels to a brackish aquifer above the partly decomposed basement rock. As a consequence, the underground water would rise, perhaps to the surface near the water course, bringing salts with it. Studies of saline seeps, and saline valley floors have usually shown that the potentiometric surface is near or above the soil surface (Teakle and Burvill, 1938; Bettenay, Blackmore and Hingston, 1964; Mitchell and colleagues, 1978). Wood's hypothesis has not been proven by rigorous experimentation, but there have been numerous observations of various aspects of the hydrologic effects of clearing which has led to a general acceptance of the hypothesis (Holmes, 1971; Peck, 1978).

Recently, Conacher (1975) proposed a throughflow model to explain salt movement to areas of accumulation. This alternative hypothesis states that salts stored in the near-surface soils are translocated by flow of groundwater perched above a shallow impermeable hard-pan or plough-pan, and form the primary source of salts found in saline seeps.

In the following sections of the paper the rising groundwater hypothesis is investigated using data from small experimental catchments in Western Australia.

EVIDENCE FROM EXPERIMENTAL CATCHMENTS

Theoretical aspects of the response of an aquifer to increased recharge due to irrigation have been well established. Peck (1975, 1976b) has recognised aspects relevant to non-irrigated agriculture in relation to both soil salinity development and reclamation. However, the absence of suitable data sets from field experiments has limited the testing or application of the theory. In the late 1960's a research program was commenced in cooperation with the Public Works Department of Western Australia to gather appropriate data in small catchments in south-west Australia. Response to clearing for agriculture in terms of altered hydrology, particularly groundwater and surface water, and concurrent changes in salt export, is outlined below for some of these catchments.

Subdued Drainage Catchment at "Yalanbee", Bakers Hill

This catchment, of 108 ha, is located on the CSIRO Experiment Station, "Yalanbee", at Bakers Hill, some 60 km east of Perth, Western Australia (see Fig. 1). Clearing for agriculture was completed in 1963 with subsequent use for crops and pastures. The landscape is gently concave and the drainage line is not naturally incised. Sandy and gravelly duplex soils overlie mottled kaolinitic clay at depths generally less than 1 m changing with depth to a pallid kaolinitic clay which continues to igneous basement rock at depths of 10 m or more. Results from this catchment are used to show the importance of changes in the potentiometric surface on the export of salt in streamflow.

TABLE 2 The annual input and output of water and salt (as chloride ion) for the Subdued Drainage Catchment, "Yalanbee", Bakers Hill, Western Australia

Calendar Year	WATER			SALT		
	Rainfall mm	Stream flow mm	Stream flow / Rainfall	Rainfall kg Cl^-/ha	Stream flow kg Cl^-/ha	Salt flow / Salt fall
1969	339	1.5	0.004	21.0	0.9	0.04
1970	522	7.7	0.015	32.4	NA	-
1971	608	4.4	0.007	40.2	10.2	0.25
1972	442	10.9	0.025	29.3	33.3	1.1
1973	668	39.1	0.059	39.3	121.3	3.1
1974	760	69.7	0.092	43.3	184.2	4.3
1975	650	39.6	0.061	35.2	601.1	17.[illegible]
1976	590	10.7	0.018	37.0	219.4	5.9

A stream gauging station was installed in June 1968 to provide daily flow data. The weir wall was seated into the mottled clay so that flow in the surface sandy layer was measured as part of the stream flow. During the next 9 years, 61 samples of stream water were taken at approximately monthly intervals when the stream was flowing to provide a measure of water quality. The output of salt was calculated as the summation of the product of stream-flow and average flow-weighted chloride content for each month. The input of salt, measured as chloride ion in rainfall, was monitored in the catchment. These inputs and outputs are given in Table 2. The saltflow/saltfall values for 1969 and 1971 are similar to values found for recently cleared catchments elsewhere on the Station. However a considerable increase in saltflow is evident from 1973 onwards.

The soil above the clay was sampled at 30 sites in the summer of 1968-69 to determine salt content. For an average depth of 0.73 metres, the total chloride content was 610 kg ha^{-1}. Between 1972 and 1976 (inclusive), when annual saltflow/saltfall ratios exceeded unity, the catchment contributed 975 kg Cl^{-} ha^{-1} to the saltflow. Thus the salt storage in the more permeable soils above the clay is not sufficient to account for the net salt export from the catchment even if it were all mobilised during this period. This result does not corroborat the hypothesis of Conacher (1975).

In May 1969, a well with water level recorder was installed 100 m upstream from the gauging station to monitor groundwater perched in the sands overlying the mottled clay. The perched groundwater was seasonal, developing in April or May as a response to rainfall, with the depth of saturation increasing as rainfall increased during the winter. In all years an area of about 12 ha of the surface sands in the catchment valley was saturated by August or September, with seepage in the sands contributing water and salt to streamflow. By November or December the well was dry. From 1968 through 1970 the perched groundwater was sampled monthly at 32 sites and chloride concentrations were always less than 250 mg ℓ^{-1}.

Also in May 1969, a potentiometric, partially penetrating well was installed into the aquifer about 60 m upslope from the stream gauging station. The water entry zone was between 7.32 m and 7.66 m below ground level, with basement rock at 10.3 m. The weekly water levels, being extracted from a continuous record of water level, are given in Fig. 3, together with cumulative rainfall. By making

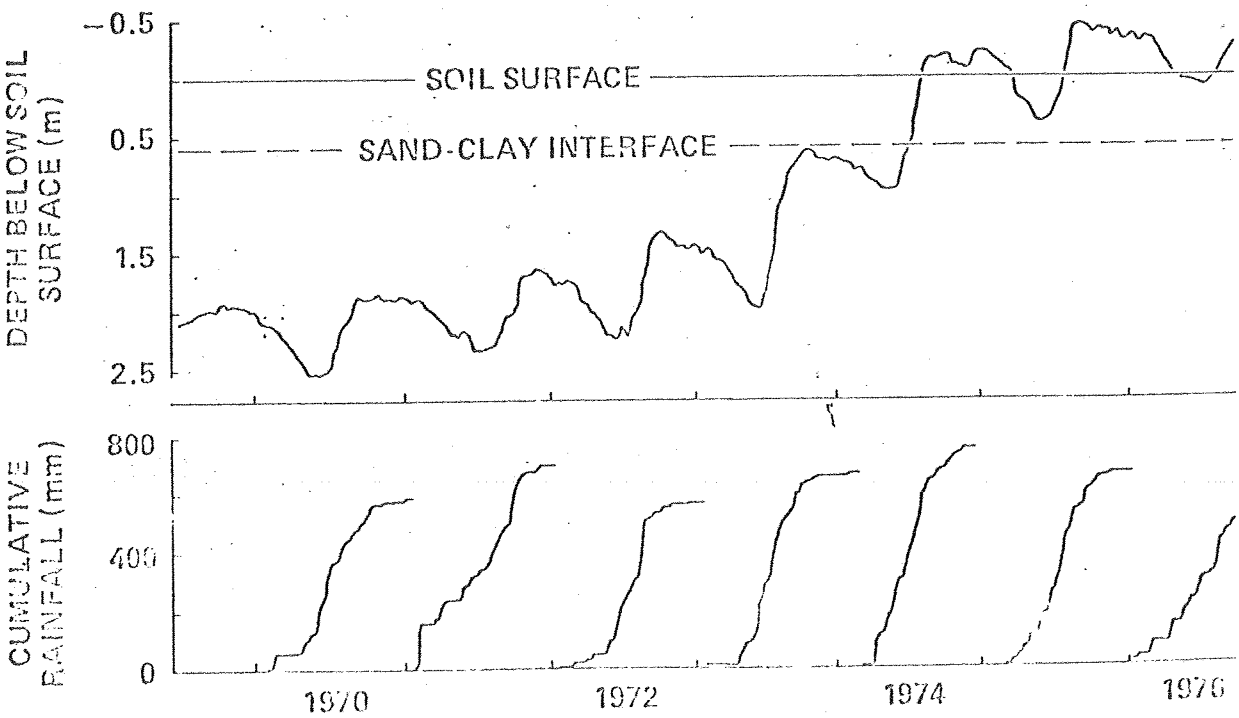

Fig. 3. The potentiometric surface of the groundwater at 7-day intervals for a well in the Subdued Drainage Catchment, and the annual cumulative rainfall based on 7-day totals.

some adjustment for the 2 m vertical height difference between the ground surface at the well and the stream gauging station, the measured increase in saltflow in 1973 (see Table 2) correlates well with the rise in the potentiometric surface of the groundwater to or above the sand-clay interface. By August 1974 the hydraulic head had risen sufficiently to indicate that the aquifer was confined and to provide a gradient for transfer of the saline (≃ 10,000 mg ℓ^{-1} chloride) groundwater to the soil surface and consequently into the stream. A further expression of groundwater leakage at the soil surface was the appearance in 1974 of saline seeps in the vicinity of the well and stream gauging station. The rising potentiometric surface suggests that there has been an increase in the proportion of the rainfall passing to the groundwater apparently as a response to clearing and pasture establishment.

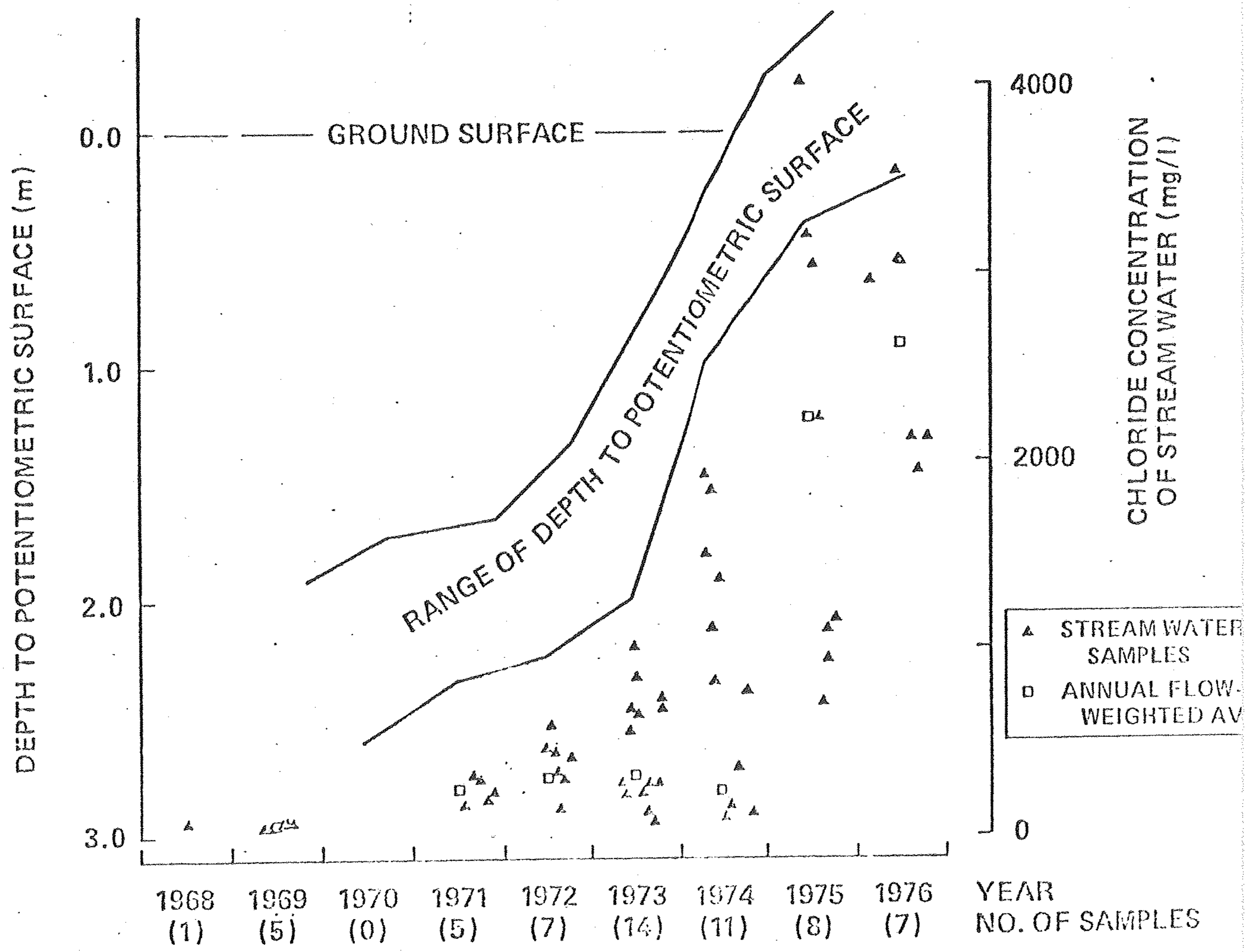

Fig. 4. The chloride concentration of stream water samples for the Subdued Drainage Catchment in relation to the range of depth of the potentiometri surface of the groundwater.

The influence of the rising potentiometric surface on stream salinity is shown in Fig. 4, where the change in the annual range of depth to the potentiometric surface of the deep aquifer has been superimposed on a scatter diagram showing the 58 measured values of chloride concentration in stream water obtained between 1968 and 1976. The increase in chloride content of stream water is directly related to the decreasing depth of the potentiometric surface below the soil surface.

TABLE 3 Annual input and output of water and salt for paired catchments at Bakers Hill, Western Australia. West Catchment was cleared for agriculture in December 1973. Water year commences in March.

Water	WATER in mm						SALT as chloride in kg ha^{-1}					
Year	Rainfall		Streamflow		Stream/Rain		Rainfall		Streamflow		Stream/Rain	
	East	West	East	West	East	West	East	West	East	West	East	West
1968*	427	427	58.2	8.6	0.136	0.020	21.7	22.2	27.9	6.1	1.29	0.27
1969*	386	386	0.0	0.0	0.0	0.0	19.6	20.0	0.0	0.0	0.0	0.0
1970	538	547	2.7	0.2	0.005	<0.001	27.3	28.4	1.5	0.1	0.05	<0.01
1971	547	562	1.7	0.0	0.003	0.0	33.4	34.5	0.7	0.0	0.02	0.0
1972	435	451	2.8	0.0	0.006	0.0	22.6	23.4	1.6	0.0	0.07	0.0
1973	643	671	27.2	1.2	0.042	0.002	37.3	39.0	12.5	0.9	0.34	0.02
1974	731	745	46.0	42.3† (6.6)	0.063	0.057† (0.009)	40.0	41.8	20.6	23.8† (4.6)	0.52	0.57† (0.11)
1975	777	765	36.0	37.9 (4.8)	0.046	0.050 (0.006)	36.0	37.6	14.7	23.7 (2.9)	0.41	0.63 (0.08)
1976	457	456	4.0	9.2 (0.4)	0.009	0.020 (0.001)	15.6	15.9	1.6	3.9 (0.2)	0.10	0.25 (0.01)
1977	484	499	0.3	2.2 (0.0)	<0.001	0.004 (0.0)	22.0	23.7	0.1	1.1 (0.0)	<0.01	0.05 (0.0)

* Streamflow measurements commenced 25 June, 1968, hence rainfall results start from that date also. Rainfall results from 25 June, 1968 to 16 July, 1969 are for a gauge located 2 km from the catchments. Average annual rainfall chloride concentrations of 5.2 mgℓ^{-1} for 1971-1977 (incl.) used to obtain saltfall for water years 1968, 1969, and 1970.

† Numbers in parenthesis are the estimated output for non-cleared condition based on pre-clearing correlation between the catchment pair.

The Paired Catchment Study at "Yalanbee"

Paired forested catchments on "Yalanbee", the CSIRO Experiment Station at Bakers Hill, Western Australia, were instrumented in 1969 to study the water and salt balances both before and after clearing for agriculture. The West Catchment, of 19.3 ha, was cleared in December 1973, sown to crop in 1974 and subsequently managed for grazing. The East Catchment, of 15.3 ha was maintained as the forested control catchment. Both are in the upland part of the landscape with markedly seasonal streams. Groundwater observation wells (11 on East, 16 on West) were installed across the lower boundary of each catchment to determine seepage loss through the deep pallid clays beneath the stream gauging weir. Ten additional wells were installed in the West catchment, particularly in a 4 hectare area of residual soils on gently sloping upland where a deep (6 m) gravelly soil profile occurs overlying mottled and pallid kaolin clays. Results from this catchment pair are used to show the response in stream outputs and groundwater levels to a land use change from forest to agriculture.

The input and output of water and salt for both catchments in the period 1968 to 1977 is given in Table 3. Using the 16 data sets available from the 6 year pre-clearing calibration period, the relationship between monthly water and salt (as chloride) outputs for the catchment pair are described by the equations

For water (in mm): Output West = 0.168 Output East - 0.3
For salt (in kg Cl^{-1} ha^{-1}): Output West = 0.263 Output East - 0.3

with correlation coefficients of regression 0.89 and 0.86 respectively.

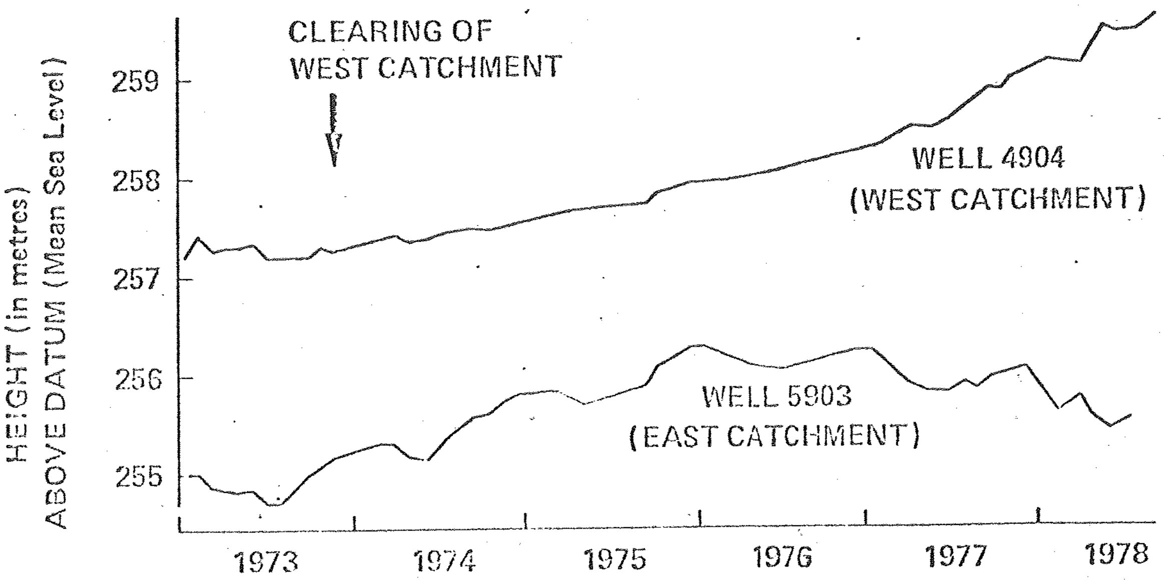

Fig. 5. Trend of groundwater levels in pallid clays for selected representative wells in the paired catchments at the CSIRO Experimental Station, Bakers Hill, Western Australia.

The post clearing data shows that actual output of salt and water from the West Catchment has increased substantially as a response to the clearing. Although the saltflow:saltfall ratio is still less than 1.0, there is a marked increase in salt loss in streamflow. The maximum post-clearing annual flow-weighted average chloride concentration for the streamflow was 63 mg ℓ^{-1}. Concentrations in the pre-clearing years exceeded this value, with a maximum of 80 mg ℓ^{-1}. The corresponding concentrations for the East catchment were 45 mg ℓ^{-1} and 57 mg ℓ^{-1} respectively. There was no indication in either catchment of seepage of high salinity groundwater into the stream. The increased proportion of rainfall salt reaching the stream due to increased run-off cannot account for the increase in salt output in the stream. The increased output is probably due to an increase in perched groundwater movement into the stream through the banks of the deeply incised surface drainage lines.

The water level data for wells 4904 and 5903 in Fig. 5 are representative of the fluctuations of groundwater level in wells across the lower boundary of the West and East catchments respectively. For the West catchment wells there has been a continuous increase in water level of about 2.4 m during the 1974-1978 post clearing period. In contrast, the water level in the East Catchment wells showed a net rise of about 1 m in 1974-75, followed by a net fall of about 0.7 m in the drier years of 1976-78.

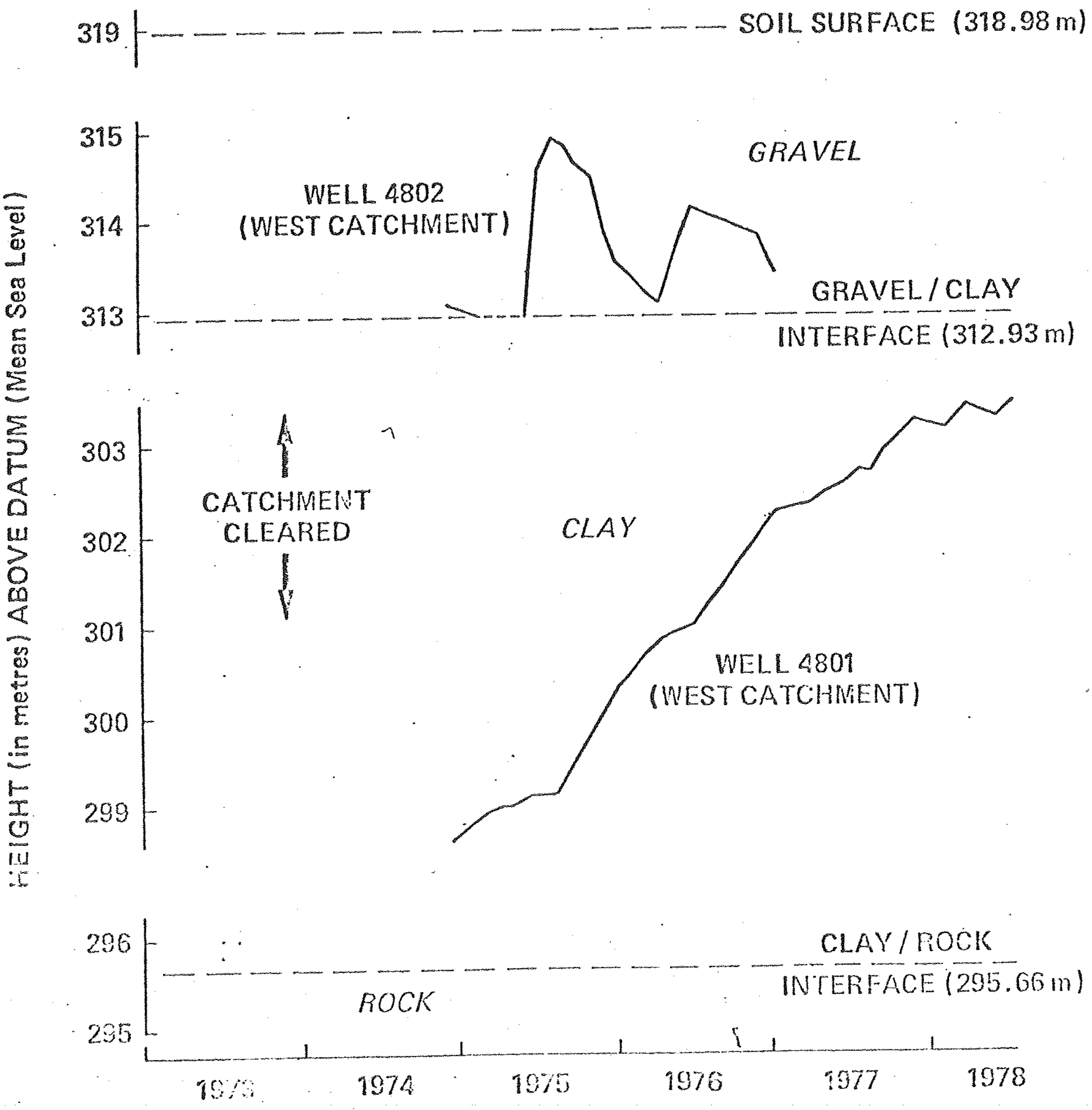

Fig. 6. Response in levels of perched groundwater in deep gravels (well 4802) and groundwater in underlying pallid clay (well 4801) following clearing of the West Catchment.

The post-clearing changes in water levels within the West catchment have varied. For example, well 4153, which was located in mid-slope with basement rock 6.6 m below ground level, has remained dry. This is possibly due to the shedding nature of the soil surface in the general area of the well leading to a dominance of run-off. In contrast a net rise of 1.5 m yr^{-1} was found in well 4801 located in 17.4 m of pallid clay beneath an extensive 6 m deep gravel soil unit in the upper part of the landscape. Well 4802 was nested with well 4801 and used to measure the perched groundwater in the gravels. The water level fluctuation for these wells is shown in Fig. 6. Assuming no evapotranspiration loss, the volume change in the gravel layer was sufficient to provide the recharge necessary for the measured rise of the deeper groundwater. Unfortunately, well 4801 was not installed prior to clearing, but a backwards extrapolation of the trend of the 1975-78 data suggests that the aquifer would have had a thickness of 1 m or less at date of clearing. The post-clearing rise in the hydraulic head may have increased the volume of flow of the deeper, saline (11,000 mg Cl^{-} ℓ^{-1}) groundwater toward potential seepage zones in lower landscape positions although none have yet appeared. The identification of this upland recharge area is considered significant.

Wights Catchment, Collie

Five small forested catchments within the watershed of the Wellington Dam, near Collie (see Fig. 1) were instrumented in 1974 to study the effect of clearing for agriculture on the salt and water balances. One pair of adjacent catchments, Wights (93.8 ha) and Salmon (81.8 ha) are located where the long-term average rainfall is 1150 mm yr^{-1}. Wights Catchment was cleared in January 1977 and sown to pasture in June 1977, while Salmon Catchment was kept as the forested control. The pre-clearing calibration relationship for the catchment pair for monthly streamflow in mm, established by Stokes (personal communication) using 3 years of data, is

$$\text{Wights Streamflow} = 0.3 + 0.89 \text{ Salmon Streamflow}$$

with a correlation coefficient of 0.986.

TABLE 4 Annual input and output of water and salt (as chloride ion) for the Wights Catchment, Collie, Western Australia, Catchment was cleared of natural forest in January and February, 1977.

Calendar Year	Input		Output		Output/Input	
	Water mm	Chloride kg ha^{-1}	Water mm	Chloride kg ha^{-1}	Water	Chloride
1974	1423	88	320	215	0.22	2.4
1975	961	74	81	146	0.08	2.0
1976	686	45	19	88	0.02	2.0
1977	934	60	152	282	0.16	4.7

Rainfall is mean of 5 gauges

The annual inputs and outputs of water and salt (measured as chloride ion) for Wights catchment in the period 1974-1977 are given in Table 4. Streamflow from Wights catchment increased by a factor of 2.4 in the first year after clearing (1977), apparently due primarily to increased run-off. This expected increase in run-off provides a mechanism for moving salt into the stream from areas of accumulation down-slope of saline seeps. Several seeps are present in the catchment associated with a partially confined aquifer. The saltflow:saltfall ratio has increased by a factor of 2.2 compared to the pre-clearing average. In the same 4 year period, the annual flow-weighted average chloride concentrations of stream water were 67, 180, 463 and 186 mg ℓ^{-1} respectively.

The increase in the salt export as a response to clearing Wights Catchment has been significant and immediate, with the source being stored salt. The expected post-clearing rise of groundwater levels occurred in a grid of wells across the catchment following the 1977 winter, although in most wells the continued rise in 1978 was more definitive. The 1977 rise would have produced only a small change in transmissivity and hence a small increase in post-winter baseflow. Although seepage produced the first streamflow in 1977 about 25 days earlier than in previous years, change in baseflow does not appear to be important in the first year after clearing since 75% of the increase in chloride ion output was exported in June, July and August. In these months, 72% of the annual streamflow occurred, being dominated by run-off. Salt accumulated in surface soils may be more important than saline groundwater as the source for the increase in salt export during the immediate post-clearing years.

A Comparison of Streamflow Quality Changes for Wights and Lemon Catchments, Collie

Streamwater quality results for Wights Catchment, and Lemon Catchment, another of the five experimental catchments in the watershed of the Wellington Dam, may be interpreted to indicate the contribution of saline groundwater to streamflow. The chloride concentration of the streamflow in 1975, when the two catchments were forested, is given in figure 7. Lemon Catchment of area 344 ha, is located east of Collie where the long-term average rainfall is 800 mm yr^{-1}. About half the catchment (184 ha) was cleared for agriculture in December 1976.

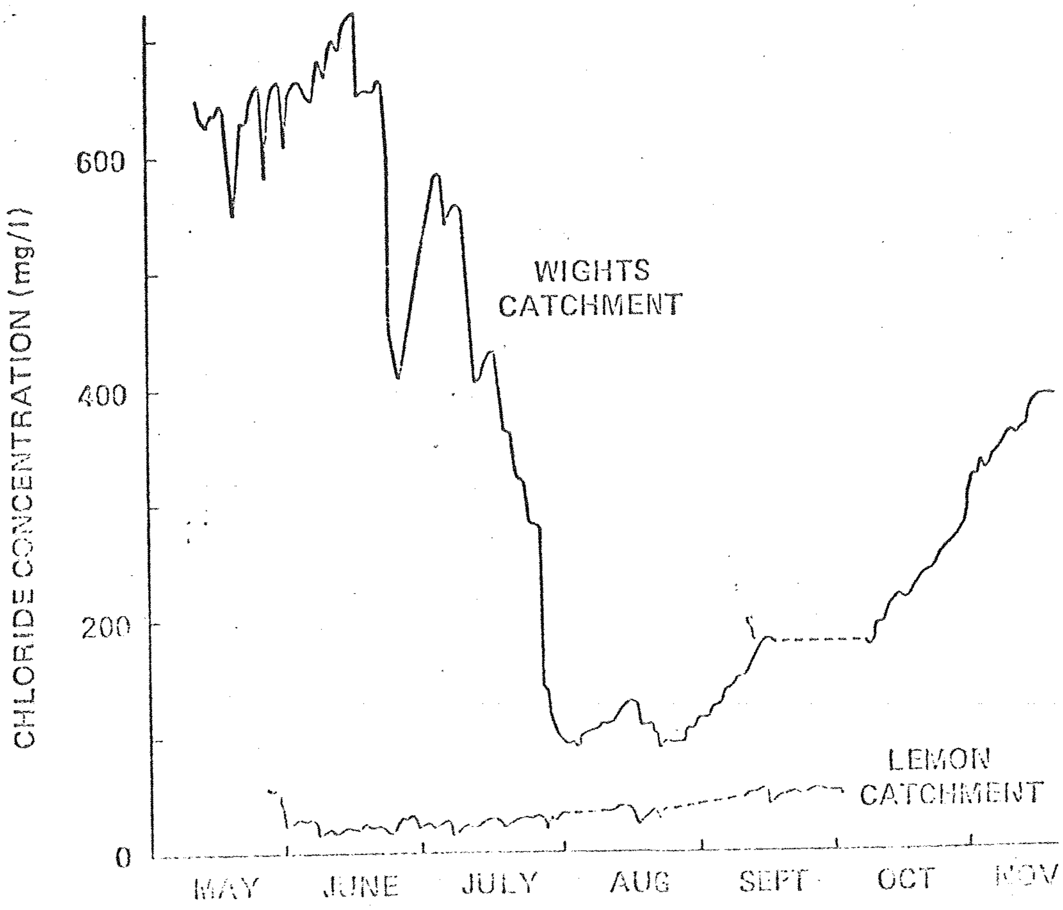

Fig. 7. A comparison of fluctuations of the chloride concentration of streamflow in 1975 for Wights Catchment (run-off plus seepage) and Lemon Catchment (run-off only), near Collie, Western Australia.

Average groundwater chloride concentrations of 780 mg ℓ^{-1} and 320 mg ℓ^{-1}, respectively, were measured for the partially confined aquifer at the two major seeps in Wights Catchment. Water from the first seep was observed in the autumn to pass directly into the stream line at a point 240 m from the stream gauging weir. The other seepage area was a further 250 m from the weir, but surface flow produced was inadequate to reach the weir directly. The seasonality of the observed flow was directly related to the rapid decrease in evaporative demand in April. The high chloride concentration of initial streamflow in Wights in 1975 indicates the dominance of the seepage contribution (Fig. 7). The subsequen reduction in chloride concentration corresponds with an increasing volume of run-off generated by winter rainfall. From mid-October onward, stream flow was less than 100 m^3 day^{-1}, and decreasing. The corresponding steady increase in stream chloride concentration is considered to reflect the increasing proportion of saline groundwater seepage contributing to that flow. The same pattern occurred in 1974 and 1976.

In Lemon catchment, by contrast, there was no seepage area. Groundwater, with 1000 mg Cl^- ℓ^{-1}, was at a depth greater than 16 m below the soil surface in the valley. Figure 7 shows that, in 1975, the chloride concentration of streamflow was low with only a small change during the period of flow. A similar pattern occurred in 1974 and 1976. In 1975 the chloride output in streamflow was 564 kg, equivalent to the chloride deposited by rain on 19 ha of the catchment. The major run-off producing area is a broad flat valley floor of 35 ha extending about 900 m upstream from the gauging station. Hence, the total chloride output could be generated by runoff. By comparison, the chloride output from Wights catchment in 1975 was more than twice the total catchment chloride input in rainfall.

Therefore the changes in salinity of streams in forested catchments provide a pattern for indicating the contribution of saline groundwater to streamflow. Wit increased recharge following clearing any development of saline baseflow should produce a change in the annual pattern of stream salinity. A careful study of Fig. 4 shows that stream salinity for the Subdued Drainage Catchment was low (60 mg Cl^- ℓ^{-1}) and uniform in 1969 when there was no saline seepage. However, in 1974, saline seepage changed the pattern to resemble the Wights type of Fig. 7, with concentrations changing from 1900 mg Cl^- ℓ^{-1} for stream-flows in April, to 150 mg Cl^- ℓ^{-1} in August, rising again to 780 mg Cl^- ℓ^{-1} in October. The annual variation of stream salinity should be a useful tool for making a preliminary assessment of the salinity hazard of induced hydrologic changes in a forested catchment, and for gauging the effectiveness of methods used to reduce or elimina seepage in a farmed catchment.

CONCLUSIONS

Removal of native, deep-rooted evergreen vegetation to cultivate rain-fed annual crops and pastures has resulted in the mobilisation of stored salts, particularly in areas of southern Australia which have a Mediterranean-type climate.

Redistribution of stored salts has resulted in loss of agricultural land, but an even more serious problem has been the deterioration of water resources. In south Western Australia there is evidence that some major rivers were once of acceptable quality, but following agricultural development have limited use for domestic, stock, irrigation and industrial purposes.

Major reservoirs, in which large capital investments have been made, are also threatened, and in some, the quality of water has deteriorated beyond recommended maximum salt levels for domestic and irrigation uses. The increases in salt yield of some catchments is of sufficient concern to water supply authorities to justify legislative control of clearing for agriculture as a politically acceptable means of arresting the deterioration of water supply quality.

Despite the enunciation in 1924 of a reasonable hypothesis for the mechanism which produces increased salt levels of streams following land clearing, it is only in the last ten years that comprehensive catchment studies have commenced to provide data which could test models to predict the effects of changed land use on stream salinity.

Using data from catchments with known clearing history, the response to clearing for agriculture has been shown to produce a significant rise in groundwater levels paralleled by increased yield of both water and chloride ion in streamflow. The rising groundwater levels indicate an increase of groundwater recharge which has the effect of increasing the volume of groundwater flow (seepage), either through increased transmissivity or increased hydraulic gradient, or both. Where the groundwater is saline, the development or increase of seepage at the soil surface results in an increase of salt output in the streamflow, leading to a net export of salt from the catchment. Increase in run-off resulting from the clearing may cause a decrease in the annual flow-weighted average stream salinity in the initial years. However, in the long-term this is not usually sufficient to keep the salinity below an acceptable level, particularly for domestic or irrigation uses. The annual pattern of streamflow quality changes provides an indicator of the contribution of perennial saline seepage to stream flow. The results presented support the rising groundwater hypothesis of Wood (1924) as an explanation for the development of saline seeps and increased stream salinity.

ACKNOWLEDGEMENTS

The authors acknowledge the discussion with colleagues in the Division of Land Resources Management, particularly Dr. A.J. Peck and Mr. D.H. Hurle, which has assisted data interpretation. The Water Resources Section of the Western Australian Public Works Department was responsible for the collection and processing of stream flow data in all catchments, and the collection of stream water samples in the Wellington watershed catchments. The co-operation of Mr. Z. Titmanis in analysing numerous water samples is appreciated as is the technical assistance of Mr. P.A. Yendle, Mr. M.I. Height and Mr. W.G. Russell.

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