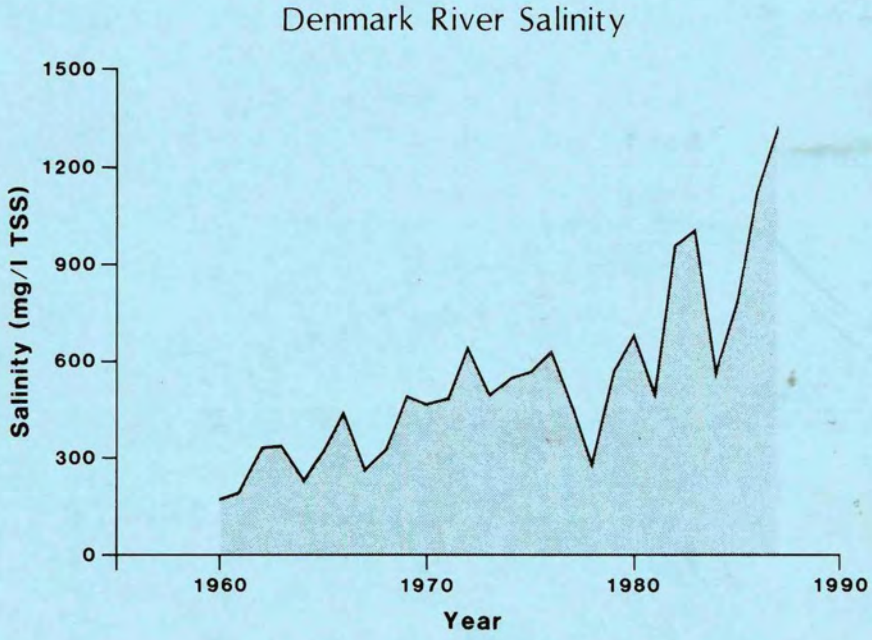
# The Impact of Agricultural Development on the Salinity of Surface Water Resources of South-West Western Australia


Denmark River Salinity

Water Authority of Western Australia
August 1988

Report No. WS 27

# The Impact of Agricultural Development on the Salinity of Surface Water Resources of South-West Western Australia

Prepared for the Steering Committee for
Research on Land Use and Water Supply by

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## Streamline Abstract

THE IMPACT OF AGRICULTURAL DEVELOPMENT ON THE SALINITY OF SURFACE WATER RESOURCES OF SOUTH-WEST WESTERN AUSTRALIA

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This report is an up-to-date, comprehensive review of stream salinisation arising from agricultural development of land in south—west Western Australia. The report starts with the history of salinity problems, going back to the earliest observations at the turn of the century. This is followed by a broad assessment of the current extent of stream salinisation. The next topic deals with causes of stream salinity, with a detailed discussion of the orgin and distribution of salts and accumulation and leaching processes. The impacts of agricultural development on individual components of the water and salt cycles and at the regional scale are then reviewed. This leads to an analysis of stream salinity trends and predictions of future stream salinity. The final sections deal with salinty management practice and highlights future needs for both management and research.

Key words; Stream salinity, agriculture, water resources, salinity management, conservation, hydrology, groundwater, catchment, soil salinity, review.

Water Authority of Western Australia, Perth, 1988, ISBN 0 7309 1751 7, xiv 69 pp, 23 figures, Water Resources Directorate, Surface Water Branch Report No. WS 27.

## Other Recent Reviews by the Steering Committee for Research on Land Use and Water Supply (Western Australia)

1. *Bauxite Mining in the Jarrah Forest: Impact and Rehabilitation.* Department of Conservation and Environment of Western Australia, Bulletin 169, 55 pp, April 1984
2. *The Impact of Logging on the Water Resources of the Southern Forests Western Australia.* Water Authority of Western Australia, Report No. WH 41, 33 pp, May 1987.
3. *Forest Management to Increase Water Yield from the Northern Jarrah Forest.* Water Authority of Western Australia, Report No. WS 3, 23 pp, August 1987.

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# *Summary*

## INTRODUCTION

Early this century it was realised that clearing of native vegetation for agriculture was causing increases in stream salinity in many areas of south-west Western Australia. In recent years considerable progress has been made in understanding the mechanisms involved in stream salinisation and in establishing methods to reverse the problem. This report aims to comprehensively review the history, impact, knowledge and trends of agriculturally-induced stream salinity in this region.

## HISTORY

The earliest reference to agricultural clearing causing stream salinity was made by locals in the Northam-Toodyay district in 1897. Soon after the completion of Mundaring reservoir in 1902, the Chief Engineer of the Goldfields Water Supply Administration, N. C. Reynoldson (1909) realised that the salinity of the reservoir was increasing rapidly, which he attributed to ring-barking and cultivation within the reservoir catchment. Railway engineers also noted increasing salinity problems in their reservoir catchments in which ring-barking had been carried out (Bleazby, 1917).

The first viable theory of the salt problem was put forward by Wood (1924). He suggested that the salt originated from the ocean, was deposited on the landscape in rainfall and dry fallout, and stored in the soil. Destruction of native vegetation allowed more water to percolate to the groundwater, which then rose, bringing salt to the surface. This general description still holds today.

The growth of agriculture was slow to 1900, with only 30 000 hectares sown to wheat at that time. Rapid expansion occurred from 1900–1930 and from 1950 onwards. The area sown to wheat is now in excess of 4.6 million hectares. Land salinisation emerged as a problem for agriculture soon after the turn of the century. However, the demand for land was so great that salinity concerns were overridden. By 1984, some 255 000 hectares or 1.6% of agricultural land was salt-affected.

After the early observations and explanations of stream salinisation, the understanding and concern of water managers became surprisingly dormant for a long period and tended to decline with new generations. From the 1930s to the late 1950s salinity was largely regarded as an agricultural problem. There was little concern for water supplies because fresh sources were generally plentiful and the problem of Mundaring Weir was considered solved by halting further land alienation and repurchasing and regenerating some cleared areas. Furthermore, the implications for nature conservation such as loss of breeding habitat for water-birds, were neither clearly understood or recognised by the general public.

The demand for water increased rapidly during the 1950s with the growth in agriculture, irrigation areas, mining and other industries, and domestic requirements. The deterioration of water resources due to salinity became increasingly apparent through the 1960s and 1970s and eventually led to the government progressively introducing controls on land alienation and clearing.

Research was initiated in the late 1960s to validate Wood's early hypothesis and to predict future salinities. Research has continued to improve the understanding of the mechanisms involved in stream salinisation following agricultural clearing, and to develop methods of halting or reversing increases in stream salinity.

## CURRENT EXTENT OF STREAM SALINISATION

A map of stream salinities of the south-west drainage division is located inside the back cover. Streams have been categorised according to fresh, marginal, brackish and saline (for definitions of these categories see Table 2). Streams arising in areas with rainfall greater than 1100 millimetres per year (mm/yr) are fresh whether forested or cleared. Fresh streams may also occur in lower rainfall areas where clearing is minor or absent. Below 900 mm/yr rainfall, streams are usually brackish or saline where clearing has been significant.

In 1985, 43% of the total surface runoff of the south-west drainage division was classified as divertible for water supply purposes. Of the divertible surface water resources, 48% was fresh, 16% was marginal, 30% was brackish and 6% was saline.

## UNDERSTANDING THE CAUSES OF STREAM SALINITY

It is now well established that the bulk of the salt in streams of the south-west drainage division was transported from the ocean to the land via rainfall. As with the ocean, the main component of stream salt is sodium chloride, being about 80% by weight. Geographic studies of atmospheric solute deposition in the south-west region have shown that chloride concentration in rainfall and chloride precipitation decrease with increasing distance from the coast. Rainfall salinities are typically of the order 10–20 milligrams per litre (mg/L) Total Soluble Salts (TSS) in the water resource catchments of the south-west.

Although some rainfall salt will be transported directly to streams, the main source of stream salt is that leached from the soil which has accumulated over previous millennia. A strong correlation of increasing soil salt storage with decreasing rainfall has been established for east of the Darling Scarp. In high rainfall areas (greater than 1100 mm/yr) soil salt storage is low and agricultural clearing has not been a significant problem for water quality. Below 1100 mm/yr rainfall, soil salt storage increases with decreasing rainfall, and agricultural clearing results in increases in stream salinity.

Considerable research has been directed towards understanding the processes of salt accumulation and leaching from a catchment. In essence, the replacement of native, deep-rooted, perennial plant species with shallow-rooted, annual agricultural species alters the water balance in favour of increased groundwater recharge. As a consequence groundwater levels rise until they intersect the valley surface. Salt previously stored in the soil is mobilised and brought to the surface or discharged directly to streams, resulting in increased stream salinity.

Analysis of catchments across the south-west region shows that clearing in areas above 1100 mm/yr will marginally increase stream salinities but, on average, salinities remain well within the fresh range. Clearing raises stream salinities from fresh to marginal in the 900–1100 mm/yr rainfall zone; from fresh to marginal or brackish in the 700–900 mm/yr rainfall zone; and to brackish in the 500–700 mm/yr rainfall zone. Stream salinities become saline following clearing where rainfall is below 500 mm/yr.

The magnitude of the stream salinity response is affected by the proportion and location of agricultural clearing. There is a clear trend for stream salinity to increase with area cleared. The rate of increase in salinity with area cleared is greater the lower the average rainfall. In low rainfall areas significant increases in stream salinity occurred in response to early clearing of the valley floors and lower slopes. Later clearing upslope led to rapid and large increases in stream salinity.

## TIME TRENDS IN STREAM SALINITY

Stream salinities in fully forested catchments have been declining over the last two decades. This decline is attributed to lower rainfall conditions causing the lowering of groundwater tables and consequently a decrease in groundwater and solute discharge.

All the major catchments of the south-west division which have been subjected to agricultural clearing and with upper reaches extending into lower rainfall areas show increasing stream salinity. The rate of increase is higher for lower rainfall areas. Streams with long periods of record indicate that salinity increase has accelerated over the last two decades. Six major rivers which are currently potable (fresh or marginal) or close to potable are continuing to deteriorate, namely the Collie, Denmark, Warren, Kent, Preston and Capel Rivers.

Attempts have been made to predict future stream salinities of some of the catchments which have the potential to be restored to or maintained at potable salinity levels. Predictions for the Collie, Helena, Denmark, Warren and Kent Rivers indicate that their salinities, without any remedial action, would increase by about 30%, 15%, 15%, 65% and 25% respectively.

Agricultural clearing typically changes the salt balance of a catchment from a state of salt equilibrium or accumulation to a state of net salt export. The high salt export rates from agricultural catchments means that, ultimately, soil salt will be leached from the catchment and stream salinity will decrease to low levels generated by atmospheric solute input. The time required to export the soil salt has been estimated to be of the order of 1000 years for low rainfall areas. In view of this long period of time, it is considered more appropriate to manage the important water resource catchments in a manner that will halt or reverse increasing salinity trends within a period of 10–30 years.

## SALINITY MANAGEMENT OF SURFACE WATER CATCHMENTS

The surface water catchments of the south-west have been classified into a number of groups depending on their salt hazard. The principal groups are low salt hazard, forested, marginal, extensively cleared and totally cleared catchments. This classification has formed the basis of salinity management strategies.

The forested catchments, particularly those with significant salt hazard, are being managed with a policy of high protection of water quality. The water resources of these catchments are fresh. The main activities in these catchments are forest operations such as clearfelling, selection logging and thinning, and bauxite mining. Extensive research programmes have been established to assess likely impacts and develop appropriate operational guidelines so as to minimise any potential increases in stream salinity resulting from these operations. Studies of the escalation of forest diseases and pests and their interaction with the various land uses are also being carried out.

The marginal catchments are those which have stream salinities within or close to the marginal category (see Table 2) and often have an increasing salinity trend. The catchments are predominantly forested, but extend inland to salt prone areas which have been partially cleared for agriculture. These catchments require active management to maintain their usefulness as water resources and biological habitat.

The most important water resource catchments in the south-west have been subjected to land alienation and clearing controls. Legislative control on the release of Crown land was imposed on the Mundaring catchment early in the century, on

Wellington, Kent and Denmark catchments in 1961, and on parts of the Preston, Capel, Blackwood, Donnelly, Warren, Gardner, Shannon, Deep and Frankland catchments in 1978. It was soon realised, however, that this action would not be sufficient to maintain satisfactory stream-salinity levels in some marginal catchments, and legislation was introduced to control forest clearing on the Wellington Dam (Collie) catchment in 1976, and the Mundaring, Denmark, Warren and Kent catchments in 1978.

Despite the above actions, stream salinities have continued to increase over the last 20 years at an alarming rate on the Collie (42 mg/L/yr), Denmark (26 mg/L/yr), Warren (15 mg/L/yr) and Kent (58 mg/L/yr) rivers. In addition the salinity of the Preston River, a potential water resource for the Bunbury region, increased at 11 mg/L/yr over the period 1965–75. Further supplementary action is required to halt the stream salinity increases if these catchments are to remain viable potable water resources for future water supplies. Partial catchment reforestation has been the most promising approach of a range of possible options. This was initiated on the Wellington Dam (Collie) catchment in 1979/80. More recently an integrated catchment management approach involving both forestry and agricultural strategies has been initiated for the Denmark catchment. The description and discussion of these strategies are the subject of a companion report (Steering Committee for Research on Land Use and Water Supply, 1989).

The extensively and totally cleared catchments include some of the major water resources of the south-west, namely the Murray, Blackwood and Avon Rivers. These rivers are now well into the brackish and saline categories and their restoration to potable levels for water supply is not an economic proposition at the present time. However, the tributaries of these catchments which are forested and yield potable water could be developed for water supply.

Small water resources suitable for development of small town water supplies can be particularly sensitive to increasing, seasonally variable stream salinities. There is a need to identify and determine the management requirements of these resources.

## OTHER PROBLEMS RELATED TO INCREASING STREAM SALINITY

Extensive land degradation and loss of conservation values has accompanied stream salinity deterioration in south-west Western Australia. These associated problems and approaches to their amelioriation are closely related to the water supply issue.

Some 255 000 hectares (ha) or 1.6% of the land that had been cleared for agriculture by 1984 has been lost to salinity. This area has increased at an average rate of about 6000 ha/yr since 1955.

Little attention has been given to the impact of salinity on conservation of lake and riverine ecosystems. It is probable that the salinity increases which have occurred in the intermediate and long rivers would have eliminated some species of aquatic invertebrates. In inland agricultural areas salinity has resulted in a loss of plant communities around swamps, lakes and rivers. Lake Toolibin, almost the last of these characteristic sheoak/paperback wetlands, supports more breeding species of waterbirds than any other wetland in south-west Western Australia. Lake Toolibin is now also threatened by increasing salinity.

## FUTURE RESEARCH REQUIREMENTS

Further research on the impact of agricultural clearing on stream salinity should include:

- Additional studies of the water and salt flows from catchments following clearing to determine the behaviour of stream salinity over time. It is necessary to know the likely duration of the phases of increasing salinity and decreasing salinity (to a new equilibrium) for a range of conditions.
- Upgrading of current models for the prediction of future stream salinities of large water resource catchments. The models should then be applied to the management priority catchments to enable a better assessment of management options and priorities.
- Research into the potential impact of the Greenhouse Effect on agriculturally-induced stream salinity.
- Attention to the impact of salinity on lake and riverine ecosystems. Most effort should be directed to identify, assess and develop management strategies for the remaining freshwater wetlands in the inland agricultural areas, which have very high conservation values and are seriously threatened by salinity.

The need for future research on the impact of agricultural clearing is limited to the areas listed above. Most resources should now be devoted to research into rehabilitation of salt-affected catchments and protection of fully forested catchments subject to non-agricultural land disturbances.

## CONCLUSIONS

- Agricultural development in south-west Western Australia has led to extensive stream salinisation to the extent that 36% of the divertible surface water resources are no longer potable and a further 16% are of marginal quality. Additionally considerable biological changes have occurred in wetlands and rivers of low rainfall areas.
- Stream salinities of a number of major rivers subjected to agricultural clearing are currently increasing at a rapid rate.
- Stream salinities of forested catchments have generally decreased over the last two decades.
- Whether or not normal agricultural development will cause increases in stream salinity depends primarily on the quantity of salt stored in the catchment. Salt storage in turn is closely correlated with annual rainfall. In areas with rainfall greater than 1100 mm/yr, agricultural clearing is unlikely to increase stream salinity beyond the fresh limit (500 mg/L TSS). However below 1100 mm/yr rainfall, stream salinities are likely to become marginal, brackish or saline, with the prognosis being worse the lower the rainfall.
- There is a clear trend for stream salinity to increase with the proportion of area cleared. The rate of stream salinity increase with area cleared is greater for lower rainfall, high salt storage zones. In low rainfall areas, a small percentage of clearing may result in significant stream salinity increases.
- Legislative controls on land alienation and clearing have been a major first step in minimising stream salinity increases on some important marginal catchments. Further supplementary catchment management, however, is required to halt or reverse the continuing salinity deterioration on these catchments.
- Six catchments have been highlighted as requiring the initiation or continuation of salinity management. These are the Collie, Helena, Denmark, Warren, Kent and Preston River catchments. The potential of a number of small water resources to develop salinity problems should be kept under review.

- Considerable progress has been made since the early 1970s in understanding the salinity problem. Future research should focus on:

  —accurate prediction of the future time course of stream salinities;

  —the potential impacts of climatic change on stream salinity and water yield;

  —identification and development of management methods for valuable conservation sites under threat of salinity;

  —techniques for the rehabilitation of important marginally salt-affected catchments;

  —protection of forested catchments which are subject to forest and mining operations, diseases and pests.

# *1. Introduction*

Throughout most of its history the development of Western Australia has relied heavily on agriculture based on annual crops and pastures. Growth in agriculture was slow from settlement of the State in 1829 to 1900, but expansion was rapid following the turn of the century.

Agricultural development involved replacing large expanses of native vegetation with cereal crops and pastures. This brought about a major environmental change largely unforseen by the settlers. Groundwaters rose beneath agricultural vegetation and brought large quantities of naturally occurring salt to the soil surface and into streams. Early observations of this phenomenon were recorded around 1900 and the mechanisms were fairly well understood by the 1920s (Bleazby, 1917; Wood, 1924). However at this time agriculture was expanding rapidly and salinisation developed primarily into an agricultural problem in which crop and pasture productivity was being adversely affected by increasing soil salinity.

It was not until the 1960s that increasing stream salinity emerged again as a major water resource concern. In the 1970s the State Government took action to protect the remaining fresh water catchments in the south-west of the State by placing controls on agricultural clearing. Current projections suggest that fresh water supplies in the Perth–Bunbury region will be fully committed early in the next century (Western Australian Water Resources Council, 1987a) at which time sources further afield will be required. There is now a recognised need to protect and manage the water resources of the south-west of Western Australia for the future prosperity of the State.

Past reviews of salinity problems in Western Australia have focused either on land salinisation (Burvill, 1947; Mulcahy, 1978; Malcolm, 1982) stream salinisation (Public Works Department, 1978, 1979) or both (Peck, 1978; Peck *et al.*, 1983).

This report provides a current review of stream salinisation resulting from agricultural development and describes its history, extent, causes and current trends. It concludes by identifying future requirements and priorities for management and research.

# 2. *The History of Salinity Problems*

## 2.1 Early Observations

Stream salinity is not a new problem in Western Australia, nor one entirely associated with the impact of European settlement of the State. A number of observations were recorded by the early settlers indicating that saline flows occurred east of the Darling Range. The first observation to this effect was noted by Ensign Dale (1830) in a 'Report of Expedition East commencing October 25, 1830'. Bunbury remarked in 1833 on the brackish pools in the Avon and Williams Rivers (G. H. Burvill, personal communication 1981). Nathaniel Ogle (1839) wrote of the alternations of salt pools and fresh streams in his 'The Colony of Western Australia—A Manual for Emigrants'. Some years later Mr E. H. Hargraves (1863 a, b), a geologist working for the Western Australian Government, left Albany in 1862 to look for goldfields from Jerramungup to the Big Bend of the Murchison. On his return, after travelling 2 200 miles, he reported that Western Australian rivers were 'beds of salt, pools of brine and brackish water', with the exception of the rivers flowing west from the Darling Range.

The impact of European settlement of Western Australia on stream water quality was first discussed at length by Bleazby (1917) and Wood (1924).

Bleazby (1917) cited a number of cases where railway water supplies had become saline. The locomotives at the time required water of less than 30 grains per gallon (430 mg/L) salt (sodium chloride) concentration. As the railways followed settlement and the traffic increased, it became necessary to excavate reservoirs. The catchments of these reservoirs were generally not protected, and following the practice in other countries, the forest trees were often ring-barked and the undergrowth was cut. As settlement increased, clearing and cultivation were extended on these catchments and within 10–12 years the reservoir water became too saline for use in locomotives.

The settlers in many districts also found that tanks they had excavated became saline following clearing and cultivation. Bleazby also noted that a few streams were perennial and maintained good quality water following clearing, but these streams were only found in higher rainfall districts.

Following the occurrence of increased salinity in railway reservoirs, Bleazby was given the task of investigating the salinity problem. From stream salinity surveys of the reservoir catchments, he was able to divert saline creeks from the reservoirs. Then, in consideration of the question of how the reservoir water could be maintained fit for locomotive use, Bleazby noted that nearly all reservoir catchments which had been ring-barked or cleared yielded water in excess of 30 grains per gallon (430 mg/L) and often as much as 1000 grains per gallon (14 250 mg/L) sodium chloride. On the other hand the stream salinity ranged from 6–10 grains per gallon (86–143 mg/L) where the catchment was still covered by virgin bush.

Bleazby presented one of the earliest hypotheses to account for the salt problem, some facets of which are still accepted today. In particular he put forward a number of important concepts:

- that native vegetation transpires rainfall entering the soil, and leaves salt in the subsoil*;
- that once a catchment is ring-barked or cleared, some portion of the rainfall has to find an outlet other than transpiration from the catchments. This could be either:
    (a) subsoil flow to creeks, taking with it salt dissolved from the soil; or

    (b) sinking in the ground, where the salt is dissolved and later brought to the surface and concentrated by solar evaporation and later washed into creeks by rain.

Bleazby argued that once a catchment yielding fresh water was found, the most certain way of ensuring the water quality was to leave the catchment in its natural state. He further suggested that a reservoir catchment that had been cleared should be allowed, at least partially, to revert to its natural state. Bleazby concluded that it might be necessary in the future to reforest railway reservoir catchment areas.

Wood (1924) gave the first clear reference to the association of agricultural clearing with stream salinity. In 1897, he heard it suggested in the Northam–Toodyay district that the destruction of the native vegetation turned the water in the creeks saline. Wood then cited some of Bleazby's examples and added some further cases, notably

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* This is only partly true as trees appear to take up the soil solution with varying degrees of exclusion of salt. Salt taken up by trees becomes concentrated in its leaves and is eventually returned to the soil in leaf litter.

the salinisation of the Blackwood River. Wood made the general statement that nearly all of the districts on the inland side of the Darling Range showed some evidence of increased stream salinity following the destruction of the native vegetation. However, he argued that stream salinisation could probably be prevented in the Darling Range, and on the upper reaches of the streams entering the Indian Ocean in the south-west, if large areas were protected in time.

Wood put forward a hypothesis to account for increases in stream salinity and the origin of the salt. His conceptual model largely holds today. Its main features are that:

- the origin of the salt is oceanic, being continuously brought in from the sea via the atmosphere and deposited on the land in rain or dry fallout;
- the killing of trees allows considerably more water to percolate to groundwater which will then rise to the surface bringing salts with it.

The modern understanding of stream salinisation processes is explained fully in Section 4 of this report.

## 2.2 Agricultural Development

Following the settlement of Western Australia in 1829, the population increased very slowly and reached only 180 000 by 1900. The growth of agriculture, in parallel with the population, was also slow. It was not until the turn of the century that agricultural development within the State increased rapidly, and huge areas of native vegetation were cleared for the planting of annual crops and pastures for cattle and sheep grazing.

Wheat farming in the south-west of the State first commenced in the 500–600 mm rainfall region and subsequently moved eastwards into lower rainfall regions. In 1900 there were 30 000 ha sown to wheat in the whole of the State. The area sown to wheat in 1985 exceeded 4.6 million hectares. The most rapid periods of development were 1900–1930 and 1955–1985 (Figure 1).

Land salinisation emerged as a problem to agriculture during the early period of expansion. The first record appeared in 1907 as a reply printed in the Journal of Agriculture under the heading 'Does clearing increase salt in ground?' The reply indicated that a farmer's query had been referred to the Government Analyst for attention. The answer suggested that it had been 'pretty conclusively proved' that the removal of trees affected water supplies and that to prevent salting it would be necessary to replant a very high proportion of the trees that had been removed.

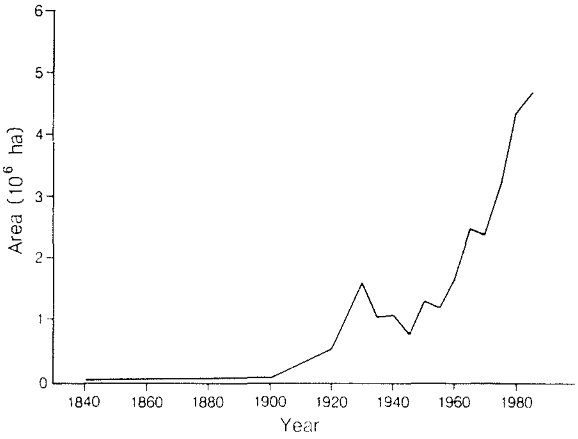


**Figure 1: Area sown to wheat in Western Australia from 1840–1985 (source: Australian Bureau of Statistics, 1986)**

In 1917 the Royal Commission on the Mallee Belt and Esperance Lands made reference to soil salt concentrations in the Esperance region. J. W. Paterson (1917), Foundation Professor of Agriculture at the University of Western Australia, outlined in considerable detail the manner in which salts accumulated in the soil and the factors influencing the level of salt which was significant for crops. He concluded, on the basis of soil analyses, that about half of the Salmon Gums area had too much salt to be of profitable use. However, the Commission criticised his report and advocated land release. Soil surveys conducted in the 1930s and 1940s showed salt problems developing in the Salmon Gums area.

As more and more land was released for agriculture, salinity concerns were frequently raised. However, the demand for new land was so great that concern for the adverse effects were overridden, resulting in the release of large contiguous blocks of land on which native vegetation was totally cleared over extensive areas.

Following its rapid expansion in the 1920s, agriculture went through a period of decline to the late 1940s. At this time salinity was considered to be essentially an agricultural problem. Little concern for water supplies was apparent because adequate sources of boiler water could always be found for railway locomotives and a problem of increasing salinity in Mundaring Weir was considered to be solved. In the 1930s and 1940s extensive soil surveys were carried out (Teakle and Burvill, 1938; Teakle, 1939; Teakle *et al.*, 1940; Burvill, 1945; Burvill, 1947). These surveys led to a greater understanding of the extent and nature of the salt problem in Western Australian soils.

The second major period of agricultural expansion occurred from the mid-1950s to the 1980s. The consequent increase in land salinisation continued to affect agriculture and further studies were carried out. Notable contributions to the understanding of the salt problem were made by Pennefather (1950) and Smith (1962). Further soil and landform analyses were carried out in the late 1950s and early 1960s drawing attention to the role of these landscape features in land salinisation (Bettenay, 1961; Bettenay *et al.*, 1962; Mulcahy and Hingston, 1961).

Surveys to gauge the extent of agricultural land affected by salinity were carried out in 1955, 1962, 1974, 1979 and 1984. In the 1984 survey it was found that 255 000 ha or 1.6% of agricultural land had been lost to salinity. The average rate of increase of salt-affected land over the five surveys is about 6000 ha per year. The proportion of agricultural land affected by salinity has more than doubled since the first survey.

## 2.3 The Development of Water Resources and a Strategy for Salinity Management

The first settlers in Western Australia relied for their water supplies on swamps, lakes and a few fresh springs close to the Swan River. Numerous wells were also put down to allow withdrawal of shallow groundwater. By the late 1840s the lakes were posing a health risk due to insect breeding and contamination from the town's cesspits. In 1875 Perth's poor drainage was blamed for 137 deaths. In 1889 it was decided to build a permanent water supply which resulted in the construction of Victoria Dam in 1891 in the Darling Range.

The discovery of gold at Coolgardie in 1892 and Hannans (later Kalgoorlie) in 1893 led to the development of the world-famous Golden Mile some 580 kilometres from Perth. From the outset, lack of water was a major problem in the Goldfields. In 1895 C. Y. O'Connor, Western Australia's Engineer-in-Chief, developed a plan to pump water to the Goldfields from a weir to be constructed at Mundaring. The weir was completed in 1902 and the first water reached Kalgoorlie in 1903.

A sequence of below average rainfall years occurred during and following the completion of Mundaring Weir and trees on an area of its catchment were ring-barked to improve inflow.

The Chief Engineer of the Goldfields Water Supply Administration, N. C. Reynoldson (1909), realised that the salinity of the reservoir had increased markedly over the period 1904–1908. He considered a number of factors likely to increase the salinity, including the leaching of salts from the reservoir basin itself, evaporation from the reservoir, ring-barking and cultivation, and annual inflow variability. He identified ring-barking and cultivation as the major cause and recommended that no further ring-barking be carried out. He further recommended that all alienated land be resumed and that all cleared land be reforested.

Following the opening of the Goldfields Water Supply Scheme in 1903, agricultural development proceeded rapidly and the settled area soon extended along the Great Eastern Goldfields Railway as far east as Merredin. In 1907 the construction of a branch main from the main water supply conduit demonstrated the value of guaranteed supplies of water for stock and domestic purposes during the long dry summers. By 1973 some 3 160 000 hectares of farmland were serviced by such branches, supplied from Mundaring and Wellington Reservoirs.

The construction of Mundaring Reservoir was followed by further development of Darling Range catchments for public water supplies. In 1924 construction began on Churchman's Brook Dam and pipehead dams on Canning River and Wungong Brook. The Canning Dam was completed in 1940 and the Serpentine Dam in 1968. These were followed by the completion of the South Dandalup Dam in 1973 and the Wungong Dam in 1982.

Harvey Dam was constructed as the first of a number of dams for irrigation supply. The dam was constructed in 1915–16 and raised in 1931. This was followed by Drakesbrook Dam which was completed in 1931 and served the Waroona irrigation area. Soon after Wellington Dam was constructed for the Collie River Irrigation Scheme. The dam was completed in 1934 and underwent subsequent raisings in 1946 and 1955–60. The latter was a major raising to provide for further expansion of irrigation and to serve the Great Southern Towns Water Supply Scheme. Increased demand for irrigation supplies in the Waroona area resulted in the construction of Samson Brook Dam in 1941. Stirling Dam was later built as the main storage for the Harvey irrigation district and was completed in 1947.

The demand for water increased rapidly from the 1950s with rapid expansion of agriculture, growth in irrigation areas and expansion in mining and industry. The increasing utilisation of available surface water resources brought about a greater concern for the effects that stream salinity was having on water resources. It was not until the increasing public awareness of nature conservation in the 1960s and 1970s that the biological problems and changes resulting from salinisation of wetlands became widely recognised. The socio-political factors affecting water resources management from the 1930s to the 1970s were described by Sadler and Cox (1987). The following is an extract from that paper, largely in its original form.

*Water resources management: the socio-political context* (Sadler and Cox, 1987)

To a chronicler aware of the observations, actions and writings of railway and water engineers and others associated with land development in the early years of the century, the attitude of government and the bureaucracy to stream salinity in the period from the 1930s to the late 1960s may suggest a surprising lack of concern. It must be appreciated, however, that agriculture has been one of the prime bases of socio-economic growth in the south-west. Because of the unswerving commitment to land development, one commentator has described the period between the 1930s and 1960s as one of 'official disbelief in the theory linking land clearing to salinity'. The period was one in which interdisciplinary communication was weak and when water engineers as well as agriculturalists were preoccupied either with development or the human problems of the great Depression and the Second World War. Nevertheless, in this period, study of the problem slowly developed from field investigation to systematic research, and water engineers began to perceive emergent salinity problems on two or three strategically important river systems.

In the 1950s and early 1960s, the Public Works Department of Western Australia perceived a need and succeeded in convincing government that land release should cease in three large river catchments that were under considerable threat from salinity. Then, recognising that clearing had gone too far in the catchment of the Wellington Dam, a water source developed for supply to inland towns and coastal irrigation, representations were made to impose control on clearing of land already released.

The clearing control measures proposed by the Public Works Department in the mid-1960s were clearly a radical proposition when government had only recently ceased releasing land and was still encouraging its development. The case was argued by the Public Works Department interdepartmentally and to government officials but was not taken into the public arena. This case was contested and rejected on the grounds that it was not proven. As a response to the failure of the argument, a period of nearly ten years followed in which effort was confined to

(a) increased research aiming to establish a more rigorous validation of the theory presented in 1924 by Wood; and

(b) establishing a more quantifiable basis for prediction of salinity increases.

That the Public Works Department's argument for control of clearing was not accepted is not surprising. Despite the long history of salinity in the region, the arguments in 1964/65 for action on the problems of the Collie River were probably inadequate for a government to support for the following reasons:

(a) the social and political issues were large, particularly when agricultural development was being vigorously encouraged;

(b) little public awareness of the significance of the stream salinity problem existed; and

(c) prevailing salinities at the time were low as a result of abnormally wet winters, and the Public Works Department was arguing a trend without a quantified prediction of outcome.

In the 1970s the tide of opinion and action on stream salinity turned quickly, spurred by a number of synergistic developments. First, researchers developed a general basis for quantifying projected salinity increases and in 1973 made such predictions for the Wellington Dam. These predictions were progressively improved through the 1970s with better quality data from the regional hydrologic network of gauging stations, automated stream samplers and pluviographs. It is probably of particular significance that, in contrast to the mid-1960s, the region was then experiencing an extended dry period, which heightened the immediate perceptions of the problem.

Second, a regional outlook had replaced the previous localized viewpoint in water planning, and the first region-wide review of resources, demands and potential water strategies was made.

This review included resource inventories, which, for the first time, allowed simple illustration of the region-wide effect of salinity on available water resources. Professional and academic institutions contributed greatly to the public articulation of this information through a variety of public seminars and conferences that attracted media interest.

Third, the worldwide increase of environmental awareness had come strongly to Western Australia, and the public was more inclined to express concern for such issues. An active forest conservation lobby vigorously picked up salinity as an argument against bauxite mining within State Forests and made salinity a more prominent public issue than the Public Works Department might have achieved unilaterally.

A series of decisions followed in quick succession in the late 1970s which established a regional strategy for salinity control based on land management. These decisions included:

(a) a regional embargo on alienation of forested State lands in river catchments;

(b) legislation to control clearing on the Collie River (Wellington Dam) catchment with payment of compensation to landholders;

(c) extension of clearing control to four other critical river catchments;

(d) reforestation in the Wellington Dam catchment through land purchase;

(e) amendment of bauxite mining agreements to prohibit mining in salt-risk areas of the forests until research has conclusively established effective rehabilitation and salinity control measures; and

(f) employment of engineering measures to adapt to increased stream salinity where control and reclamation measures were not sufficient.

Despite the severity of some of these measures and the concern expressed by landholders at the time clearing controls were introduced, the dominant public reaction has been that such action was necessary. In retrospect most would agree that this action should have occurred sooner.

# 3. *The Current Extent of Stream Salinisation*

## 3.1 Definitions and Measurement of Stream Salinity

Stream salinity is a loosely-used term usually referring to the concentration of dissolved salts in stream water. Peck *et al.* (1983) provided a stricter definition of salinity as the concentration of the major ions ($Na^+$, $K^+$, $Ca^{++}$, $Mg^{++}$, $Cl^-$, $HCO_3^-$, $CO_3^=$ and $SO_4^=$) in a solution.

Stream salinity may be expressed in a number of ways depending on the method of measurement. The most accurate method for determining the salinity of a particular water sample is to sum the measured quantities of the individual ions, which is expressed as Total Soluble Salts (TSS), in units of milligrams per litre (mg/L). In addition to the major ions given by Peck *et al.* (1983) above, the Water Authority of Western Australia includes dissolved silica in its measurement of TSS. This is the measurement of TSS generally referred to in this report.

TSS can also be estimated by measuring the electrical conductivity (EC) of water. This may be done for a collected sample or continuously within a stream. The electrical conductivities for waters of similar ionic composition can be reliably correlated to TSS. An EC-TSS correlation is normally carried out within each river basin or, if enough data are available, for individual streams. The electrical-conductivity method has considerable advantages for measuring stream salinity. Data can be continuously recorded which allows accurate determinations of the flow-weighted mean stream salinity and salt load. The recommended SI units for electrical conductivity are milliSiemens per metre (mS/m).

Another method of expressing stream salinity that is in common use is Total Dissolved Solids (TDS). The measurement involves filtering the sample to remove any sediment and then weighing the residue after evaporation. Usually there is only a small difference between TDS and TSS, due to the non-major ions. TDS is also expressed in units of mg/L.

In the south-west of Western Australia, the dominant anion is chloride. Historically this ion was frequently the only one measured and stream salinity is still occasionally expressed in chloride concentration.

## 3.2 Classification of Stream Salinity Levels

Water supplies in south-west Western Australia have a range of uses including domestic, commercial, industrial, irrigation and farm livestock. The dominant uses are domestic (31%) and irrigation (39%) (Western Australian Water Resources Council, 1986). In addition water resources provide 'instream' uses such as habitat for plants and animals of aquatic ecosystems.

Water salinity criteria for irrigation are imprecise because of the varying roles of plant, soil and climatic factors. In general terms problems are not usually encountered when the EC is less than 75 mS/m (about 500 mg/L TSS). Above this value problems increase to become severe at >300 mS/m (about 2000 mg/L TSS) (Ayres and Westcott, 1976; George, 1983).

Guidelines for drinking water quality in Australia have been issued recently by the National Health and Medical Research Council and Australian Water Resources Council (1987) and are summarised in Table 1 for the relevant substances.

It is clear from Table 1 that some flexibility is built into the guidelines to take account of local water quality conditions. This is possible because the guideline values are based on taste considerations and not health risk. Some health risk has been associated with sodium but there is currently insufficient evidence to determine a guideline value based on health considerations. The following extract from WHO (1984) summarises the present situation regarding the health risk associated with sodium.

'There is evidence that high dietary intakes of sodium play a significant role in the development of hypertension among genetically susceptible members of the population; in addition, there is some evidence that drinking-water with moderate sodium levels (100 mg/L) may be associated with an elevation of blood pressure in children. It is not known, however, if the reported small blood pressure increases are significant in terms of the development of early hypertension. It is questionable whether the low intake of sodium from drinking-water relative to that from food could be responsible for a significant additional effect. At present, there is insufficient evidence to justify a

**Table 1: Guidelines for drinking-water quality in Australia**

| Substance | Guideline value (mg/L) | Comment |
|---|---|---|
| Chloride | 400 | The WHO (1984) guideline value of 250 mg/L for chloride is based on the taste threshold in drinking water and was determined on the understanding that chloride levels are generally low, especially in natural surface water.<br>In many parts of Australia water with chloride concentrations above the WHO guideline value of 250 mg/L are common, usually in association with high sodium concentrations. While concentrations of up to 500 mg/L are necessarily accepted by some communities, a change in the taste of beverages may be detected at concentrations above 400 mg/L and accordingly a guideline value of up to 400 mg/L is considered appropriate. |
| Sodium | 300 | Sodium is a common component of drinking waters in Australia, particularly those of groundwater origin, and is frequently associated with high chloride concentrations. The WHO (1984) guideline value for sodium is based on taste considerations as sodium levels in drinking water are generally only a small contributor to dietary sodium and no specific level based on health considerations could be recommended.<br>As a consequence of the considerable difficulty in reducing the high sodium content of Australian water, the WHO (1984) guideline value of 200 mg/L is considered inappropriate for general application throughout Australia. As a result a guideline value of 300 mg/L for sodium has been adopted to provide consistency with the guideline values adopted for its frequently associated characteristics, chloride and total dissolved solids, yet ensure palatable water for consumers. |
| Total dissolved solids (TDS) | 1000–1500 | Many Australian waters have characteristically high levels of dissolved solids, the most common of which are sodium bicarbonate and chloride, and calcium and magnesium bicarbonates and sulphates.<br>Taste thresholds vary widely depending on the particular dissolved solids present. Supplies containing a TDS level of 1000 mg/L are generally acceptable, on the basis of taste considerations. However, TDS levels of up to 1500 mg/L can be acceptable in areas where better quality water is not locally available and where other water supplies cannot be procured at reasonable cost. Above 1500 mg/L taste generally renders water unacceptable to consumers. |

guideline value for sodium in water based on health-risk considerations.

Persons suffering from hypertension or congestive heart failure may require a sodium-restricted diet, and in such cases the intake of sodium from drinking-water may be of greater significance.'

Of the three criteria listed in Table 1, the chloride guideline value would generally be the first exceeded in south-west Western Australia. Here, a chloride concentration of 400 mg/L corresponds to about 730 mg/L TSS, which is well below the TDS recommended guideline values of 1000–1500 mg/L.

A general water resources salinity classification used by the Australian Water Resources Council (1986) is given in Table 2. This forms the general basis for classifying water resources in Western Australia. The fresh and marginal categories are regarded as potable resources.

The biological effects of increasing salinity are not well documented, especially at lower levels (i.e. fresh to brackish). However, in general terms the more saline a water body, the fewer species of plants and animals it supports.

In this report stream salinities are dicussed in terms of 'flow-weighted mean annual stream salinity' (unless otherwise stated) which in the text may be simply abbreviated to 'stream salinity'.

**Table 2:**
**Water resources salinity classification**

| Category | Resource salinity |
|---|---|
| Fresh | Less than 500 mg/L TSS |
| Marginal | Greater than 500 mg/L TSS but less than 1500 mg/L TSS or less than 600 mg/L chloride* |
| Brackish | Greater than 1500 mg/L TSS or 600 mg/L chloride but less than 5000 mg/L TSS |
| Saline | Greater than 5000 mg/L TSS |

* In south-west Western Australia 600 mg/L chloride is equivalent to about 1 070 mg/L TSS

## 3.3 Ionic Composition of Streams

The percentage of each major ion in stream water in the south-west of Western Australia is listed in Table 3.

The data are grouped into three sets of basins, 601–602, 603–609 and 610–616 (shown as basins 1–16 in Figure 2). Comparisons of these sets show a strong regional similarity for all the major ions. Chloride and sodium clearly dominate the ionic compositions, accounting for about 80% by weight. The relative compositions of ions also closely match those of rainwater and sea water, supporting the view that the salts have been derived from the ocean.

**Table 3:**
**Percentages of major ions by weight**
(adapted from Loh *et al.*, 1983)

| Major Ion | Esperance to Albany Coast (601–602)* | Denmark to Blackwood (603–609) | Busselton to Swan Coast (610–616) | Sea-water |
|---|---|---|---|---|
| Chloride | 52.9 | 50.8 | 52.8 | 55.1 |
| Bicarbonate | 2.7 | 6.7 | 5.8 | 0.4 |
| Sulphate | 6.0 | 4.8 | 4.5 | 7.7 |
| Nitrate | 0.2 | 0.5 | 0.6 | - |
| Sodium | 28.6 | 26.7 | 26.6 | 30.6 |
| Potassium | 0.7 | 0.7 | 0.6 | 1.1 |
| Magnesium | 3.9 | 4.5 | 4.8 | 3.7 |
| Calcium | 1.6 | 2.0 | 2.3 | 1.2 |
| Silica | 3.5 | 3.2 | 1.9 | - |

* river basin numbers

The proportion of chloride in stream water tends to increase as the salinity increases. Bicarbonate ions, conversely, are a larger component in low salinity (<150 mg/L TSS) stream water.

## 3.4 Current Stream Salinities

A broad appreciation of the current state of streams in the south-west of Western Australia can be gained from the salinity map inside the back cover. In this map the streams have been classified according to the categories of Table 2 from water quality data for the period 1981–85.

The water quality information refers to that collected at registered stream gauging stations which provide continuous flow and regularly sampled salinity data. The classification is based on annual flow-weighted mean salinities, averaged over five years of record. It is assumed that the salinity category upstream of the gauging station is the same as that determined at the station as far upstream as the next gauging station (if one exists) or as far as a major stream bifurcation. More detailed knowledge of the salinity variation over the full river networks is only possible with intensive sampling programmes such as those carried out for the Shannon, Warren and Donnelly River basins (Collins and Barrett, 1980) and the Denmark and Kent River basins (Collins and Fowlie, 1981). To be of continuing value, these basin surveys would need to be updated periodically. It should also be noted that annual stream salinities are highly variable, depending largely on rainfall variations. This has not been allowed for in the map of stream salinities.

The salinity of a main stream course at any point depends on contributions from the upstream catchment. Generally tributaries are fresh where rainfall is greater than 1100 mm/yr whether the land is cleared or forested. Fresh streams extend to lower rainfall areas where clearing is minor or absent. Below 900 mm/yr rainfall, streams are usually brackish or saline where clearing has been significant.

The salinities of the main stream courses often decrease significantly in moving downstream. For example the upper Warren River is largely saline in the rainfall zone below 900 mm/yr but is marginal at its outlet to the ocean. This characteristic is important for the development and management of surface water resources in south-west Western Australia and is not a common feature in other parts of the world (e.g. the Murray River in eastern Australia increases in salinity with distance downstream).

## 3.5 Divertible Surface Water Resources and their Salinities

An inventory of the quantities and salinities of the water resources of Western Australia has been compiled by the Western Australian Water Resources Council (1984, 1986). The inventory only included divertible water resources, minor sources were excluded.

In general divertible water resources are those from which water can be removed on a sustained basis using current technology and are suitable for urban, irrigation and other major uses. An essential requirement for many divertible surface water supplies to be sustainable is that suitable dam sites are available for developing storage reservoirs to regulate flows of rivers which are intermittent or ephemeral. In this respect the south-west division has sufficient topographic relief and sufficiently incised river valleys to form suitable dam sites.

Minor sources are those which are generally too small or too widely distributed to be economically developed for a major water supply. Examples of minor surface sources are roof runoff, farm dams, and roaded and paved catchments.

In the south-west drainage division there are 19 river basins (Figure 2). For the purposes of water resources assessment, some of these river basins have been grouped into water resource regions, of which there are seven in the south-west division (Figure 2). The areas and populations of the water resource regions and of the river basins within the regions are shown in Table 4.

A detailed breakdown of the surface water resources of the south-west division is given in Table 5. Listed in this table are mean annual flows; divertible resources, subdivided into fresh, marginal, brackish and saline categories; developed resources; constrained resources; and unutilised resources. Mean annual basin flow here refers to the sum of the mean annual flows of all the major rivers and tributaries in a basin, measured at the point where the flows are greatest. In the Yarra Yarra and Ninghan basins, the mean annual basin flow exceeds the actual basin outflow because of stream losses. Constrained surface resources are those that cannot be fully developed for water supply purposes. For example the construction of a dam could flood a valley of environmental importance or with valuable farmland.

**Table 4: Areas and populations of the water resource regions and river basins of the south-west drainage division**

| Region | River Basin | No. | Area (km2) | Population (at 30.6.84) |
|---|---|---|---|---|
| Esperance | Esperance Coast | 601 | 20 550 | 10 550 |
| Albany | Albany Coast | 602 | 18 340 | 27 800 |
| | Denmark R. | 603 | 2 700 | 3 700 |
| | Kent R. | 604 | 2 490 | 1 000 |
| | Frankland R. | 605 | 5 920 | 3 100 |
| | | | 29 450 | 35 600 |
| Warren-Blackwood | Shannon R. | 606 | 3 420 | 2 100 |
| | Warren R. | 607 | 4 360 | 3 700 |
| | Donnelly R. | 608 | 1 690 | 5 150 |
| | Blackwood R. | 609 | 22 550 | 30 050 |
| | | | 32 020 | 41 000 |
| Busselton-Harvey | Busselton Coast | 610 | 2 995 | 15 250 |
| | Preston R. | 611 | 1 140 | 28 400 |
| | Collie R. | 612 | 3 640 | 17 450 |
| | Harvey R. | 613 | 2 200 | 6 850 |
| | | | 9 975 | 67 950 |
| Perth-Mandurah | Murray R. | 614 | 8 537 | 22 750 |
| | Swan Coastal | 616 | 4 200 | 3 150 |
| | Perth Metro. Area | * | 5 363 | 969 100 |
| | | | 18 100 | 995 000 |
| Moore | Moore-Hill Rivers Coast | 617 | 24 445 | 10 600 |
| Avon | Avon R. | 615 | 115 300 | 48 700 |
| | Yarra Yarra | 618 | 41 760 | 4 700 |
| | Ninghan | 619 | 22 900 | 500 |
| | | | 179 960 | 53 900 |

* is a component of the Murray R. and Swan Coastal Basins

From Table 5 it is apparent that 43% of the surface water resources are divertible. Of the divertible water resources, 30% are brackish and 6% are saline, while 64% are potable—48% fresh and 16% marginal. Much of this resource in the south-west drainage division is available to meet future needs—70% of the potable, divertible water resources are currently undeveloped and unconstrained.

The divertible surface water resources of the Esperance and Avon regions are small and largely non-potable. The divertible resources of the Moore region are limited and only 25% are potable. The formerly significant surface water resources of the Albany region have deteriorated in quality over time and now the potable resources are very limited, with more than half being marginal.

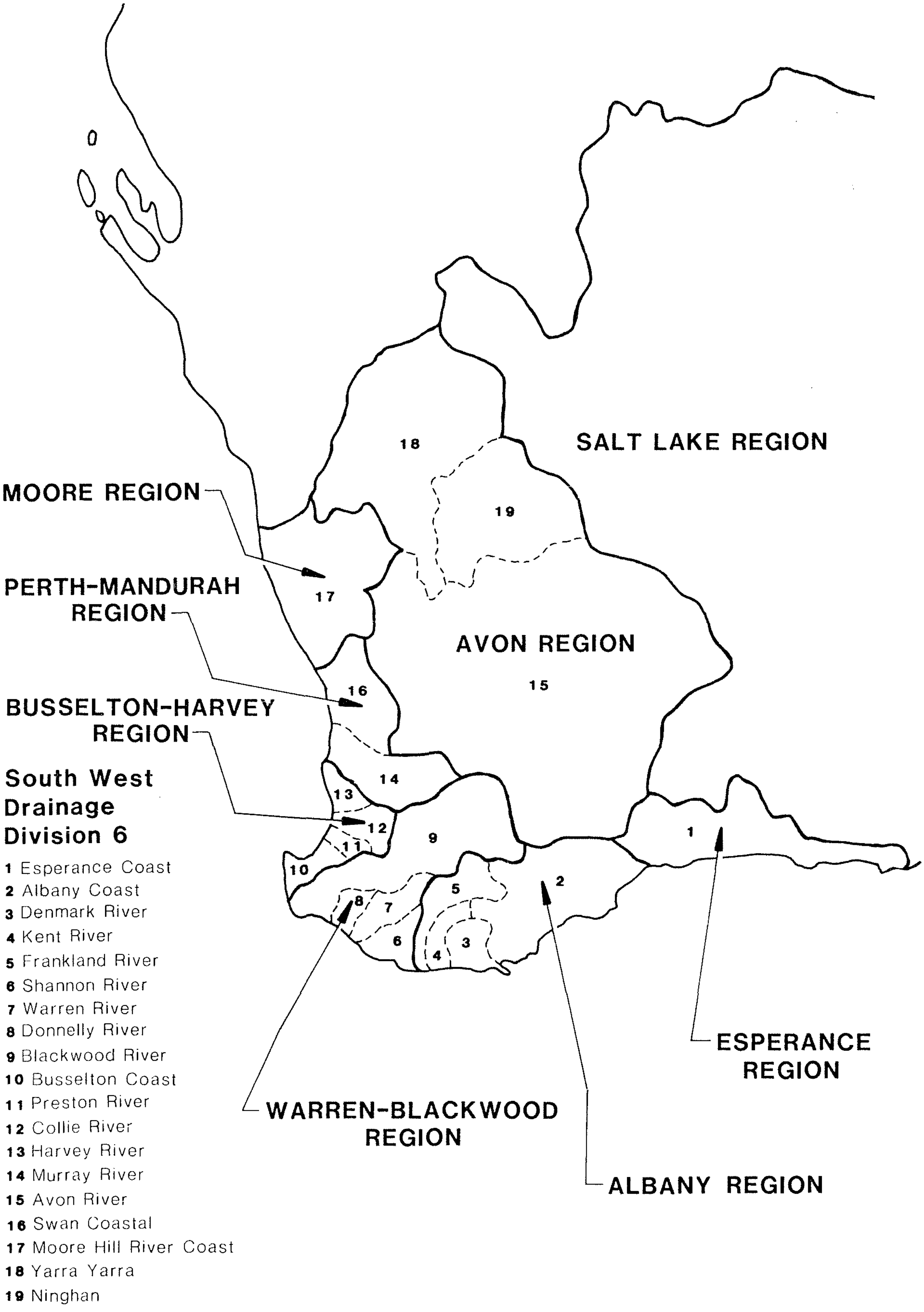


**Figure 2: River basins and water resource regions of the south-west drainage division**

## Table 5: A summary of the surface water resources in the south-west drainage division (units: million cubic metres)

| Region | River Basin | Mean annual basin flow | Divertible Resources | | | | | Potable resources | Constrained resources | Developed resources | Undeveloped and unconstrained |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Fresh | Marginal | Brackish | Saline | Total | | | | |
| Esperance | Esperance Coast | 110 | 1 | 0 | 10 | 0 | 11 | 1 | 0 | 0 | 1 |
| Albany | Albany Coast | 330 | 4 | 9 | 35 | 25 | 73 | 13 | 0 | 2 | 11 |
| | Denmark R. | 210 | 17 | 36 | 20 | 0 | 73 | 53 | 0 | 0 | 53 |
| | Kent R. | 170 | 14 | 0 | 60 | 0 | 74 | 14 | 0 | 0 | 14 |
| | Frankland R. | 200 | 1 | 0 | 120 | 0 | 121 | 1 | 0 | 0 | 1 |
| | | 910 | 36 | 45 | 235 | 25 | 341 | 81 | 0 | 2 | 79 |
| Warren-Blackwood | Shannon R. | 640 | 249 | 0 | 0 | 0 | 249 | 249 | ? | 0 | 249 |
| | Warren R. | 440 | 50 | 245 | 0 | 0 | 295 | 295 | ? | 1 | 294 |
| | Donnelly R. | 350 | 163 | 0 | 0 | 0 | 163 | 163 | 0 | 0 | 163 |
| | Blackwood R. | 1060 | 90 | 18 | 320 | 0 | 428 | 108 | 0 | 1 | 107 |
| | | 2490 | 552 | 263 | 320 | 0 | 1135 | 815 | ? | 2 | 813 |
| Busselton-Harvey | Busselton Coast | 470 | 89 | 0 | 0 | 0 | 89 | 89 | 0 | 0 | 89 |
| | Preston R. | 180 | 110 | 0 | 0 | 0 | 110 | 110 | 50 | 2 | 58 |
| | Collie R. | 380 | 62 | 142 | 30 | 0 | 234 | 204 | 30 | 78 | 96 |
| | Harvey R. | 330 | 162 | 0 | 0 | 0 | 162 | 162 | 0 | 87 | 75 |
| | | 1360 | 423 | 142 | 30 | 0 | 595 | 565 | 80 | 167 | 318 |
| Perth-Mandurah | Murray R. | 720 | 151 | 0 | 160 | 0 | 311 | 151 | 60? | 46 | 45 |
| | Swan Coastal | 540 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| | Perth Met. Area | * | 217 | 10 | 77 | 100 | 404 | 227 | 25 | 167 | 35 |
| | | 1260 | 369 | 10 | 237 | 100 | 716 | 379 | 85 | 213 | 81 |
| Moore | Moore-Hill Coast | 180 | 9 | 6 | 9 | 36 | 60 | 15 | 0 | 0 | 15 |
| Avon | Avon R. | 280 | 1 | 0 | 8 | 3 | 12 | 1 | 0 | 1 | 0 |
| | Yarra Yarra | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Ninghan | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 360 | 1 | 0 | 8 | 3 | 12 | 1 | 0 | 1 | 0 |
| | TOTALS | 6670 | 1391 | 466 | 849 | 164 | 2870 | 1857 | 165 | 385 | 1307 |

* Included in Murray R. and Swan Coastal

The three remaining regions of the south-west, the Perth-Mandurah, Busselton-Harvey and Warren-Blackwood regions, have moderately large potable resources. Of these the Warren-Blackwood has the largest total and potable resources but the least developed because of their distance from major population centres and irrigated areas. The potential water supplies of this region may be constrained to some extent due to the inception of the Shannon and Warren National Parks. The Busselton-Harvey and Perth-Mandurah regions both have significant developed potable resources. In the Busselton-Harvey region 56% of the potable surface resources are undeveloped and unconstrained. In the Perth-Mandurah region only 22% of the potable surface water resources are undeveloped and unconstrained.

# 4. *The Causes of Stream Salinity*

## 4.1 Origin of Salts

Bleazby (1917) provided the first reported speculation on the origin of soil and stream solutes. He suggested that 'the land of Western Australia may have emerged slowly from the sea, remaining for a lengthy period awash, with the result that by the constant evaporation of the salt water under the strong sun, a layer of salt was deposited which is still retained in the soil.' This concept was challenged by Wood (1924) who saw no 'evidence of saline beds such as might be expected if the sea had been over the land in recent geological times'. Wood also dismissed the suggestion that the decomposition of country rocks had released the salts because there were insufficient chlorides in the rocks to account for the salts in water. Peck and Hurle (1973), using the data of Bettenay *et al.* (1964), supported this view, showing that weathering of rock minerals would contribute less than 1 kg/ha/yr chloride. Wood was the first to put forward the now accepted explanation that, in south-west Western Australia, salt is transported from the ocean through the atmosphere to be deposited in rain, dry powder or dew. The salt would be derived from very fine spray formed by the strong breezes which lash the tops of waves. The spray would evaporate and the fine residue of salt would be transported inland by the persistent south-westerly winds of the region. Wood noted that rainfall salinities of 40 mg/L TSS were not exceptional on the western slopes of the Darling Range.

Studies in Europe and America have since demonstrated that the sea surface is the major source of atmospheric solutes in these regions. The process of entrainment of material from the sea surface, its injection into the atmosphere, and its transport and deposition to the land surface have been investigated in considerable detail and reviewed by Cryer (1986).

In 1926 rainfall salinity data were obtained at various sites in south-west Western Australia (Wood and Wilsmore, 1928). Rainfall salinities and deposition rates ranged from an average of 30 mg/L and 218 kg/ha/yr NaCl at coastal sites to 12 mg/L and 23 kg/ha/yr at inland sites.

More detailed geographic analysis of atmospheric solute inputs was reported by Hingston (1958) and Hingston and Gailitis (1976). Strong geographic variations were observed showing both decreasing chloride concentration in rainfall and decreasing chloride precipitation with shortest distance from the coast (Figure 3). Large quantities of chloride (>100 kg/ha/yr) were precipitated at coastal sites, decreasing to 50 kg/ha/yr 30 km inland, and to 10 kg/ha/yr at very inland sites. At most coastal and near-coastal locations, the contribution of terrestrial dust to atmospheric solute inputs was found to be small, with the possible exception of $Ca^{++}$ from calcite in dust from dunes. In the central south-west and south-eastern regions, and particularly at locations near salt lakes, terrestrial sources of ions were considered to be predominant.

## 4.2 Distribution of Salt in Soils and Groundwater

The primary contribution to salt in stream water is that leached from soil. Therefore, considerable efforts have been made to determine regional and local distributions of soil salt. These studies provide the necessary understanding of salt accumulation and export processes to predict the outcomes of current and future land use and management activities.

### 4.2.1 Measures of soil salt storage

Three measures of soil salt are commonly referred to (Stokes *et al.*, 1980; Johnston *et al*, 1980):

(i) soil salt storage (kg/m$^2$): the mass of TSS per unit land surface area;

(ii) soil salt content (kg/m$^3$): the mass of TSS per unit bulk volume of soil;

(iii) soil solute concentration (mg/L): the total mass of TSS per unit volume of soil water.

Measures (ii) and (iii) may be applied to a small soil sample or averaged over a soil profile. Soil solute concentration may be seasonally variable due to seasonal changes in soil water content.

### 4.2.2 Geographic distribution

The geographic distribution of soil salt content was first discussed in detail by Dimmock *et al.* (1974) with respect to the Darling Range. Soil cores of some 40 laterite profiles to 40 m depth and covering a rainfall range of 560–1350 mm/yr were analysed for salt content. Salt storages were

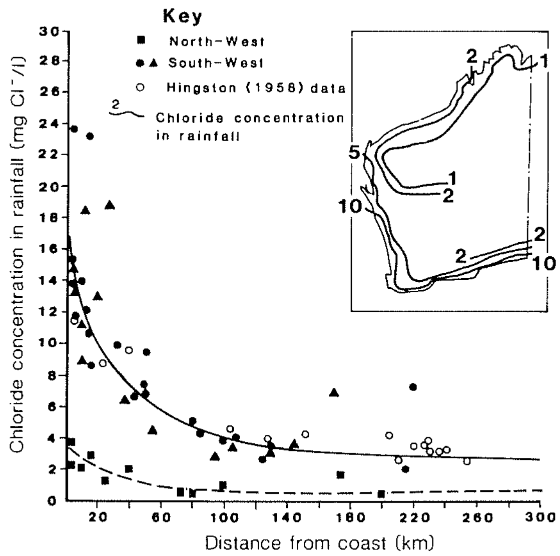


Figure 3a: Decrease in chloride concentration in rainfall with shortest distance from the coast (adapted from Hingston and Gailitis, 1976)

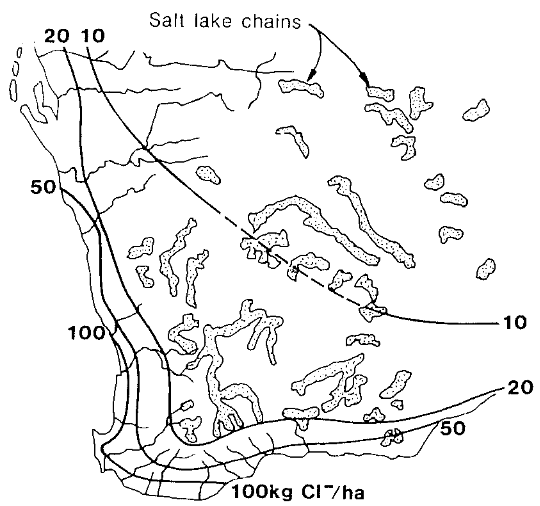


Figure 3b: Chloride precipitated over south-west Western Australia during 1973 (kg Cl⁻/ha) (adapted from Hingston and Gailitis, 1976)

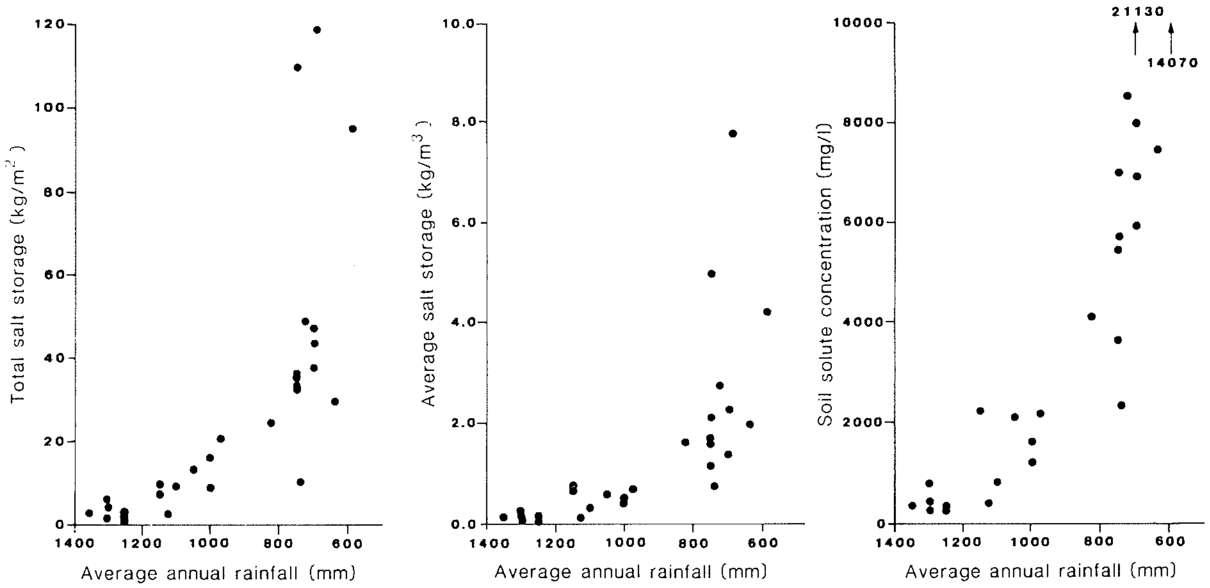


Figure 4: Variation of soil salt storage characteristics with average annual rainfall (after Stokes *et al.*, 1980)

found to increase systematically with decreasing annual rainfall, ranging from an average of 17 kg/m$^2$ above 1000 mm/yr to 95 kg/m$^2$ at 600 mm/yr.

Stokes *et al.* (1980) examined a larger set of salt storage data in the northern Darling Range. They found that, as well as soil salt storage, average soil salt content and average soil solute concentration also increased with decreasing rainfall (Figure 4).

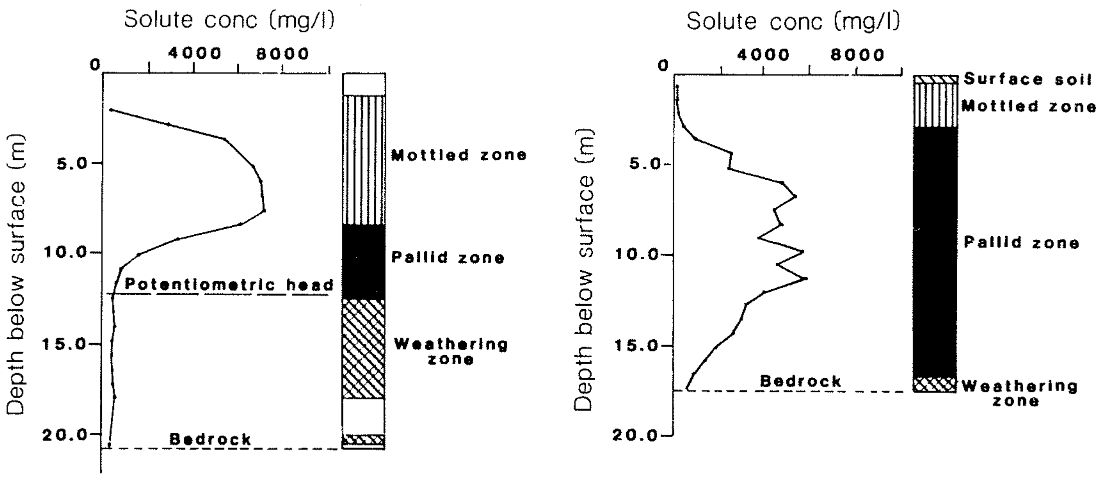
Salt content distribution in the northern Darling Range was investigated by Slessar *et al.* (1983) and Tsykin and Slessar (1985). Their data from 327 boreholes confirmed that a low salt content zone extends east from the Darling Scarp to approximately the 1100 mm rainfall isohyet. In this area the average salt content was 0.16 kg/m$^3$. The salt content increased in a near-exponential manner with distance inland from the Scarp to at least the 750 mm rainfall isohyet. The average soil salt content in the 750–1100 mm rainfall zone was 0.79 kg/m$^3$. Both distance from the Darling Scarp and mean annual rainfall were strongly correlated with average soil salt content. However there was also high local variability of soil salt content.

The non-linear salinity-rainfall relationship of the northern Darling Range was apparent but not so well-defined further south in the Manjimup Woodchip Licence Area (Johnston *et al.*, 1980). In this area 161 boreholes were drilled to bedrock and analysed for salt content. Salt storage, average salt content and average solute concentration all varied inversely with annual rainfall, although there was no discernible trend above 1050 mm/yr annual rainfall. High salt contents were found in many profiles in the high rainfall area.

### 4.2.3 Classification and occurrence of soil salinity profiles

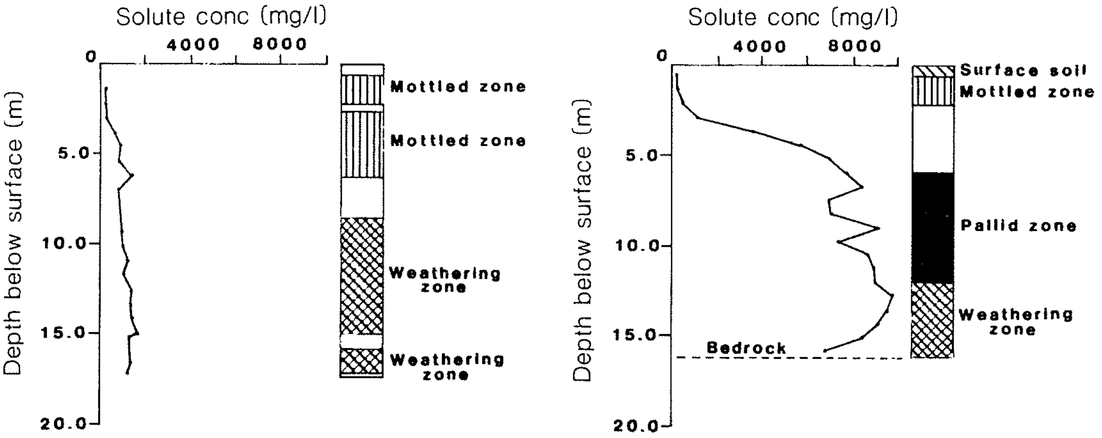
Two basic types of soil salinity profiles were described by Johnston *et al.* (1980) as 'monotonically increasing' and 'bulge' profiles (Figure 5). Some properties of these profiles are described in the following.

Monotonic salinity profiles accounted for about



(a) Profile showing a bulge in the unsaturated zone and a low uniform salinity in the saturated zone.

(b) A bulge salinity profile in a completely unsaturated soil.



(c) A monotonically increasing profile with low salinity

(d) A monotonically increasing profile with an extensive accumulation of salt.

**Figure 5: Common types of soil profile salt distribution** (adapted from Johnston *et al.*, 1980)

one third of profiles in the Manjimup Woodchip Licence Area. Typically the salinity increased almost linearly from near the soil surface to some depth below, beyond which it was fairly constant. These profiles included some of low salinity, implying relatively good leaching and others with high salt contents. Well-leached profiles were most common in the high rainfall areas. Poorly-leached profiles were typical of drier areas and were rarely found in soils with a saturated zone.

Bulge salinity profiles were defined as those having a maximum salinity at an intermediate depth in the profile (Johnston *et al.*, 1980). The maximum to minimum solute concentration was commonly about 10, and the vertical extent of the bulge typically varied between 2 and 15 m. Soil solute concentrations usually remained fairly uniform within the saturated zone and the depth of unsaturated zone appeared to be a primary factor influencing the dimensions of the bulge. Bulges occurred in profiles which were totally unsaturated as well as those partially saturated. Bulges in totally unsaturated profiles were less pronounced and there was no interval of constant, low salinity below the zone of accumulation.

Similar distributions of salt in profiles were found in the Bauxite Mining Areas of the northern Darling Range, where slightly more than 50% of profiles were classified as monotonic, all but two being of low salinity (Johnston, 1981).

Examination of salt profiles in the eastern Murray catchment (450-530 mm/yr rainfall) showed that the depth of soil profile determined its type (Johnston and McArthur, 1981). Increasing and uniform salt profiles were typical of shallow soils (<4 m) whereas all profiles greater than 10 m depth showed bulge profiles.

### 4.2.4 Distribution of salt within soil horizons

The lateritic profile is commonly divided into the following morphological zones (Johnston *et al.*, 1980): surface soil, gravel, duricrust, mottled zone, pallid zone and weathering zone. In the bauxite mining areas of the northern Darling Range, Johnston (1981) found that the pallid zone had the highest average salt content (0.51 kg/m$^3$) and concentration (1505 mg/L) while the duricrust had the lowest average salt content (0.02 kg/m$^3$) and concentration (250 mg/L). Salinities close to half of that of the pallid zone were found in the other horizons.

### 4.2.5 Topographic variation of soil salinity

Although soil salinity generally increases with decreasing rainfall there is high local variability. Some of the local variability has been explained by position in the landscape but the trends are not always consistent.

Dimmock *et al.* (1974) found that significantly higher soil salinities occurred in valley floors and lower slopes than in high slope and divide locations. In the Manjimup Woodchip Licence Area, Johnston *et al.* (1980) found that the divide and upper slope positions had lower salinities than valley, lower slope and upper slope gully sites. A similar trend of increasing salinity from divide to valley was noted in the bauxite mining areas (Johnston, 1981).

A situation contrary to this trend has been recorded in the Yarragil catchment by Herbert *et al.* (1978), where 81% of the total salt occurred in soils of the upper slopes and divides.

Recent analyses by E. N. Tsykin (personal communication, 1988) have shown that in the Alcoa bauxite lease area salt storages in wide 'bulb-shaped' valleys are generally significantly greater than in narrow 'linear' valleys. He proposes that the high salt storage results from poor drainage, and the low salt storage is a consequence of unimpeded drainage.

### 4.2.6 The influence of soil texture on soil salinity

Early soil surveys (Teakle, 1939; Teakle *et al.* 1940; Burvill, 1945) found that 'heavier' surface soils were more salty and that there was a good correlation between the clay content and salt content of soils. Similar observations were noted by Hingston and Bettenay (1961) and Bettenay *et al.* (1964) for the Merredin area. Schofield *et al.* (1985) also drew attention to the role of soil texture in salt accumulation by showing the high salt accumulation in a clayey soil profile compared to that in a sandy profile (Figure 6) located less than 100 metres apart in the Del Park research catchment (1300 mm/yr rainfall).

### 4.2.7 Distribution of groundwater salinities

The distribution of groundwater salinities was analysed for 25 sites in the south-west by Stokes *et al.* (1980). For sites under native forest vegetation, groundwater salinity increased with decreasing rainfall (Figure 7). For the uncleared sites above 1100 mm/yr rainfall, groundwater salinities were less than 500 mg/L TSS and averaged about 300 mg/L TSS. Below 1100 mm/yr rainfall, groundwater salinities of uncleared sites were less than 2000 mg/L TSS and averaged about 1200 mg/L TSS.

Groundwater salinities were considerably higher at sites subjected to agricultural clearing and less than 900 mm/yr rainfall, ranging from 4009 mg/L TSS to 15 606 mg/L TSS, and averaging about 6000 mg/L TSS. On these sites the groundwater salinities approached the mean soil solute concentrations of the soil profile.

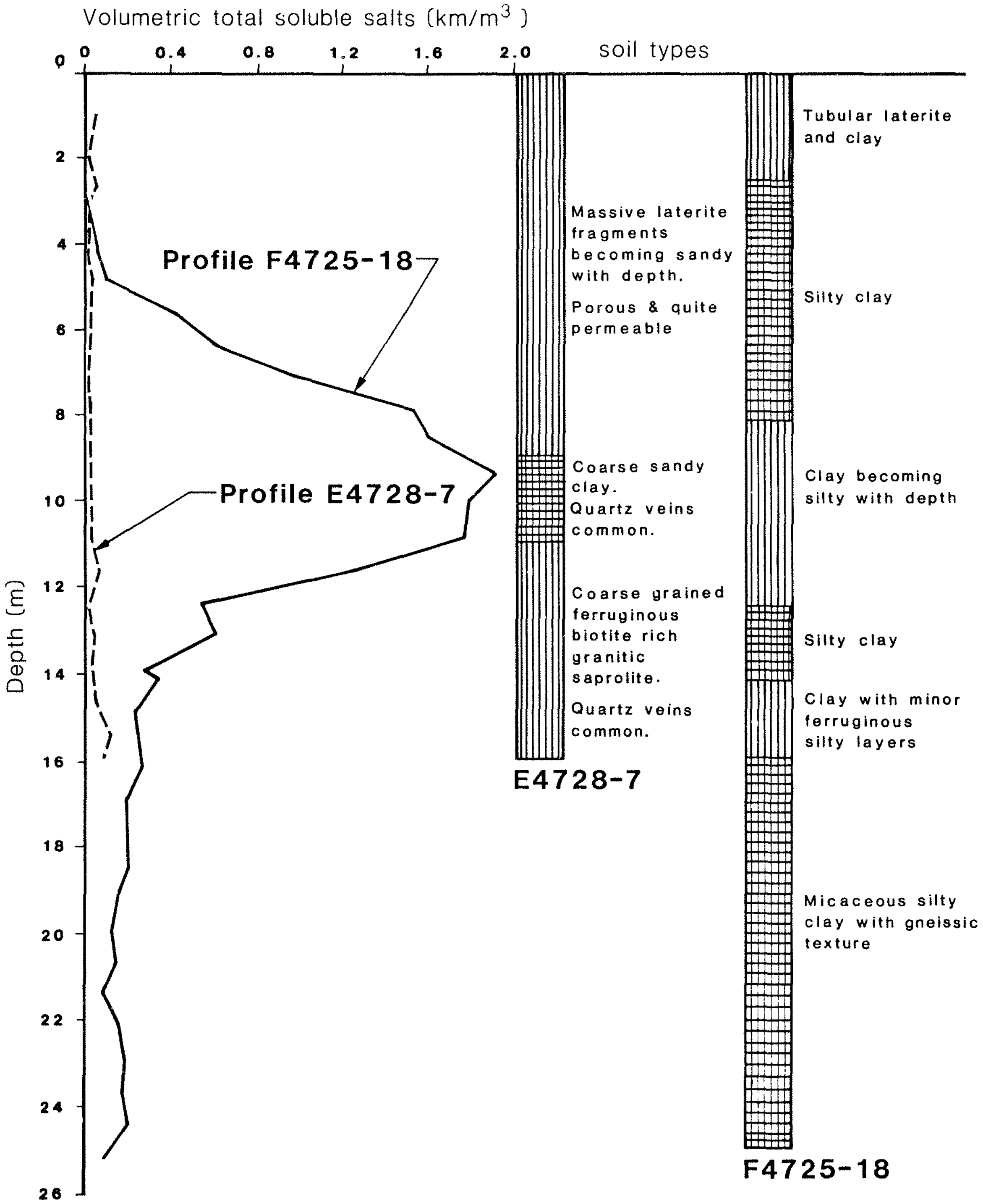


**Figure 6: Comparison of salt accumulation in coarse and fine-grained soil profiles**
(after Schofield *et al.*, 1985; data supplied by Alcoa of Australia)

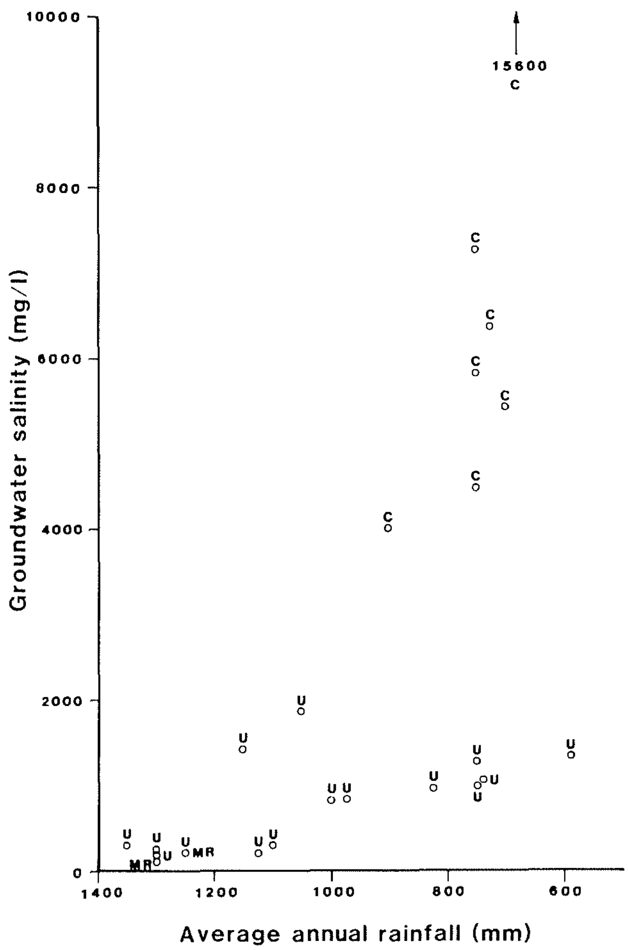


**Figure 7: Groundwater salinity versus rainfall for uncleared (U), cleared (C) and mined and rehabilitated (MR) sites** (after Stokes *et al.*, 1980)

## 4.3 Accumulation and Leaching of Soil Salt

### 4.3.1 Mechanisms of water and salt movement in Darling Range profiles

Although the mechanisms of salt transport in soils are relatively well understood theoretically and practically at the laboratory scale, the comprehension of salt accumulation, movement and discharge from a landscape is somewhat limited. Over the last decade, however, considerable progress has been made in the understanding of water and salt movement through deeply weathered, unsaturated profiles of the Darling Range. Before describing these studies in more detail, a brief mention is made of the mechanisms of salt transport.

#### *Mechanisms of salt transport*

Salt in the soil solution can move by molecular or ionic diffusion, due to the concentration gradients within the solution; or by convection, due to the mass flow of the soil solution. The processes of diffusion and convection can occur simultaneously, either in the same direction or in opposition. The transport of salt is further complicated by hydrodynamic dispersion, which is the mixing process during flow due to different flow velocities through the pore space. The differences in flow velocities and diffusion in the direction of decreasing concentration results in a dispersion of solutes. Transport of salts may also be affected by exchange or adsorption onto the surfaces of soil particles. Chloride is generally regarded as non-reactive while sodium undergoes exchange in some soils.

#### *Accumulation of soil salt*

Salt input at the soil surface is transported into the soil via infiltrating water. Salt output from the soil is via throughflow and groundwater discharge or through absorption by roots of vegetation. Vegetation uptake and return of salt to the soil is largely cyclic and generally can be ignored in the soil salt balance. When salt input exceeds salt output there will be salt accumulation in the soil and vice versa. In native forest there is, at present, a small net discharge of salt in high rainfall areas but a strong accumulation of salt in low rainfall areas. There is a high net discharge of salt in areas cleared for agriculture.

The distribution of salt in the soil profile (see section 4.2) is influenced by a number of factors, including magnitude of salt input, average annual rainfall, depth of soil, presence or absence of saturated zones, slope, and soil properties such as texture, structure and permeability.

A mathematical analysis to predict the form of salinity profiles was undertaken by Watson (1982). He utilised a one-dimensional steady-state model with simultaneous water and solute mass balance to predict salt profiles. The model assumed input of salt in rainfall and water uptake by plants. The inclusion of solute diffusion-dispersion in the model resulted in the prediction of salt bulges as well as monotonic profiles. Some observed salt profiles could not be predicted by the model, one possible explanation being the injection of low salinity water at depth via movement through preferred pathways.

*Analyses of water flow rates and salt transport mechanisms based on soil chloride distribution*

A steady-state diffusion-convection model was developed and applied to interpret chloride concentrations observed at four deep (15–26 metres) forested sites in the Darling Range by Peck *et al.* (1981). The purpose of the analysis was to characterise flow rates, source strengths (water extraction or injection) and the relative contributions of diffusion and convection to solute transport through each profile. Measurements of solute concentration and water content with depth were obtained on cored samples. Three bulge profiles and one monotonically increasing salt profile were examined.

In the monotonic profile diffusion was negligible compared to convection. The water flux density was relatively high but decreased fairly uniformly to 110 mm/yr at the water table at nine metres. It was concluded that water extraction (presumably by vegetation) took place throughout the unsaturated profile. More than 80% of rainfall was lost within one metre depth from the surface and 9% reached the water table.

For the three bulge profiles, chloride diffusion became comparable to convection in the vicinity of the salt bulges. Water extraction was inferred to occur to the depths of the bulge maxima (about 6 metres) but beyond this depth water injection was inferred. It was proposed that water movement down preferred paths from a surficial perched aquifer may account for the water injection into the profile at depth. Two of the bulge profiles were from high rainfall sites (1150 mm/yr). At these sites 14% and 17% of rainfall infiltrated to two metres depth but less than 1% reached six metres. The other bulge profile was a lower rainfall site (800 mm/yr). Here only 2% of rainfall passed through the soil at two metres and only 0.06% at six metres.

Johnston (1987a) used the steady-state solute model of Peck *et al.* (1981) to investigate subsurface hydrology in the Collie experimental catchments (see Section 5 and Figure 8). In the two western, high rainfall catchments (Salmon and Wights) all 12 profiles were of the bulge type. In the three eastern catchments 17 profiles were bulge and three were monotonic.

Relatively high water flux densities occurred at greater depths in the western catchments due to higher rainfall and lighter texture subsoils. However, long-term vertical water flux densities were small compared with estimated groundwater recharge rates (Peck and Williamson, 1987), implying a dominant contribution by preferred flow mechanisms. Johnston (1987a) postulated that preferred flow paths were widely distributed in the landscape, suggesting that large definable areas of enhanced recharge were unlikely to exist. The monotonic profiles of the lateritic duricrust uplands of the eastern catchments suggested high permeability but water flux densities did not exceed 1 mm/yr, significantly less than rates of recharge to groundwater elsewhere in the catchments.

An intensive study involving twelve profiles in a 700 m$^2$ area of Salmon catchment (Figure 8) was reported by Johnston (1987b). Eight of the profiles were of the bulge type in which water flux densities were estimated to reduce to 2–7 mm/yr at five metres depth below ground.

Four profiles were monotonic and had relatively high estimated water flux densities of 50–100 mm/yr throughout the unsaturated zone. These four profiles were fairly closely grouped and may be associated with a large structural discontinuity of unknown origin. Groundwater observations confirmed that preferential local recharge occurred in this area. Small groundwater mounds were observed to build up following rainfall events and decay within two to five days. Water velocities of order one metre per hour suggested macropore flow. Saturated conditions near the surface, thought necessary for macropore flow, were observed to be very transient.

The precise nature and relative contribution of the local preferred recharge was not adequately determined. However, some consequences of the proposed mechanisms were highlighted:

- most of the recharge appears to bypass the large stores of soluble salts, indicating that clearing would have little impact on vertical leaching of salts;
- shallow-rooted agricultural plants may not be appropriate for reducing recharge at sites where preferential flow is dominant since rainwater percolates quickly to great depths.

### 4.3.2 Discharge of salt to streams

The discharge of salt to streams generally takes place by three mechanisms: direct runoff; groundwater discharge; and throughflow discharge.

Direct runoff salt discharge is the transport of salt input from the atmosphere directly to streams without being stored in the soil.

Groundwater discharge of salt to streams generally occurs in high rainfall (>1100 mm/yr) forested areas and in agricultural areas which have been cleared for a long time. The quantity of groundwater discharge is a small percentage of streamflow but the quantity of salt discharged by groundwater can be a high proportion of the stream salt load (Stokes and Loh, 1982; Turner *et al.*, 1987).

Throughflow discharge of salt can occur in two ways. The first is the leaching of salt in the surface soil principally by perched saturated throughflow. This mechanism, with direct runoff salt discharge, would contribute most of the salt to streams of low rainfall forested catchments where groundwater is well below the stream level.

The second method of throughflow discharge was proposed by Silberstein (1985) and Stokes (1985). During the summer months salt is transported from a permanent saline groundwater to the surface soil horizon by an upward water potential gradient. The upward water potential gradient can be due to the upward pressure gradient that exists at various points within a deep groundwater system and/or capillary action in the unsaturated zone which is driven by soil water evaporation at the ground surface. These processes are particularly prevalent in lower landscape areas close to streams where groundwater potentiometric surfaces are above or within a few metres of the ground surface.

Williamson *et al.* (1987) calculated that 82% of salt discharged from Wights catchment seven years after clearing was via the shallow perched groundwater system. Since the salt export from this system was significantly greater than the pre-clearing total salt storage of the zone, the authors concluded that salts were being exported from the subsoil and discharged through the shallow perched groundwater system.

# 5. *The Effects of Agricultural Development on the Components of Water and Salt Cycles*

A programme to carry out detailed studies of the effects of agricultural development on catchment hydrological and salinity processes was initiated in 1971 in the Collie basin with financial support from the Australian Water Resources Council Research Programme. Five small catchments (<4 km$^2$) were established by 1974, two in high rainfall areas and three in low rainfall areas (Figure 8). Three of the catchments, Wights, Lemon and Dons were treated in 1977 and Salmon and Ernies were retained as controls.

The treatments can be summarised as follows:

HIGH RAINFALL CATCHMENTS

| | |
|---|---|
| *Salmon* | control |
| *Wights* | totally cleared, planted with grass and clover. |

LOW RAINFALL CATCHMENTS

| | |
|---|---|
| *Ernies* | control |
| *Lemon* | lower half (53%) totally cleared, planted with grass and clover |
| *Dons* | 38% partially cleared for three strategies |
| i) | parkland, stand density reduced to 25 stems/ha, leaf area index reduced from 1.2 to 0.1; |
| ii) | strip cleared on the contour to leave uncleared strips of 30 m between cleared strips of 100, 150 and 300 m width (uncleared to cleared ratios of 0.3, 0.2 and 0.1); |
| iii) | cleared on valley and lower slope plus either the lateritic ridge or gravelly midslope area. |

The results of these studies have been published in a special issue of the Journal of Hydrology (A. J. Peck and D. R. Williamson, Editors, 1987). Some of the more pertinent results are included in the remainder of this Section.

## 5.1 Hydrological Changes

The replacement of deep-rooted, perennial native vegetation with shallow-rooted, annual agricultural plants has consequences for all terrain components of the hydrological cycle. In nearly all cases in south-west Western Australia, this development leads to increases in stream salinity. The effects on individual hydrological components are discussed briefly.

### 5.1.1 Net precipitation

Net precipitation is the amount of rainfall arriving at the soil surface. The effect of agricultural development is to increase net precipitation by decreasing interception loss by vegetation. Few measurements of interception loss exist in south-west Western Australia. A value of 13% of rainfall for forest interception was obtained by Williamson *et al.* (1987) for Wights catchment. These authors assumed that the interception loss from the established pasture was negligible compared to errors in rainfall measurement. This implies that net precipitation would increase by 13% of rainfall as a result of the agricultural development of this catchment.

### 5.1.2 Transpiration

Native vegetation is likely to transpire more water than agricultural crops and pastures because it is deep-rooted and perennial (Dunin, 1986). No direct comparative measurements of vegetative water use between areas of native forest and areas converted to agriculture, in similar conditions, have been made in Western Australia.

Greenwood *et al.* (1985) measured differences in transpiration between pasture and various eucalypt species (*E. globulus, E. cladocalyx, E. maculata, E. leucoxylon, E. wandoo*) which had been planted on agricultural land above a saline seep. The annual transpiration of the above plantation species averaged 2100 mm. The plantations utilised considerable amounts of water in excess of the 684 mm annual rainfall, from either within or outside the planted sites. The annual evapotranspiration under pasture was considerably lower at 390 mm (57% of rainfall). Similarly low values of evapotranspiration were recorded by Nulsen (1984) for four common agricultural species, wheat, barley, lupins and subterranean clover. In this case the average evapotranspiration was 58% of rainfall during the growing season, although there were significant differences between species and sites.

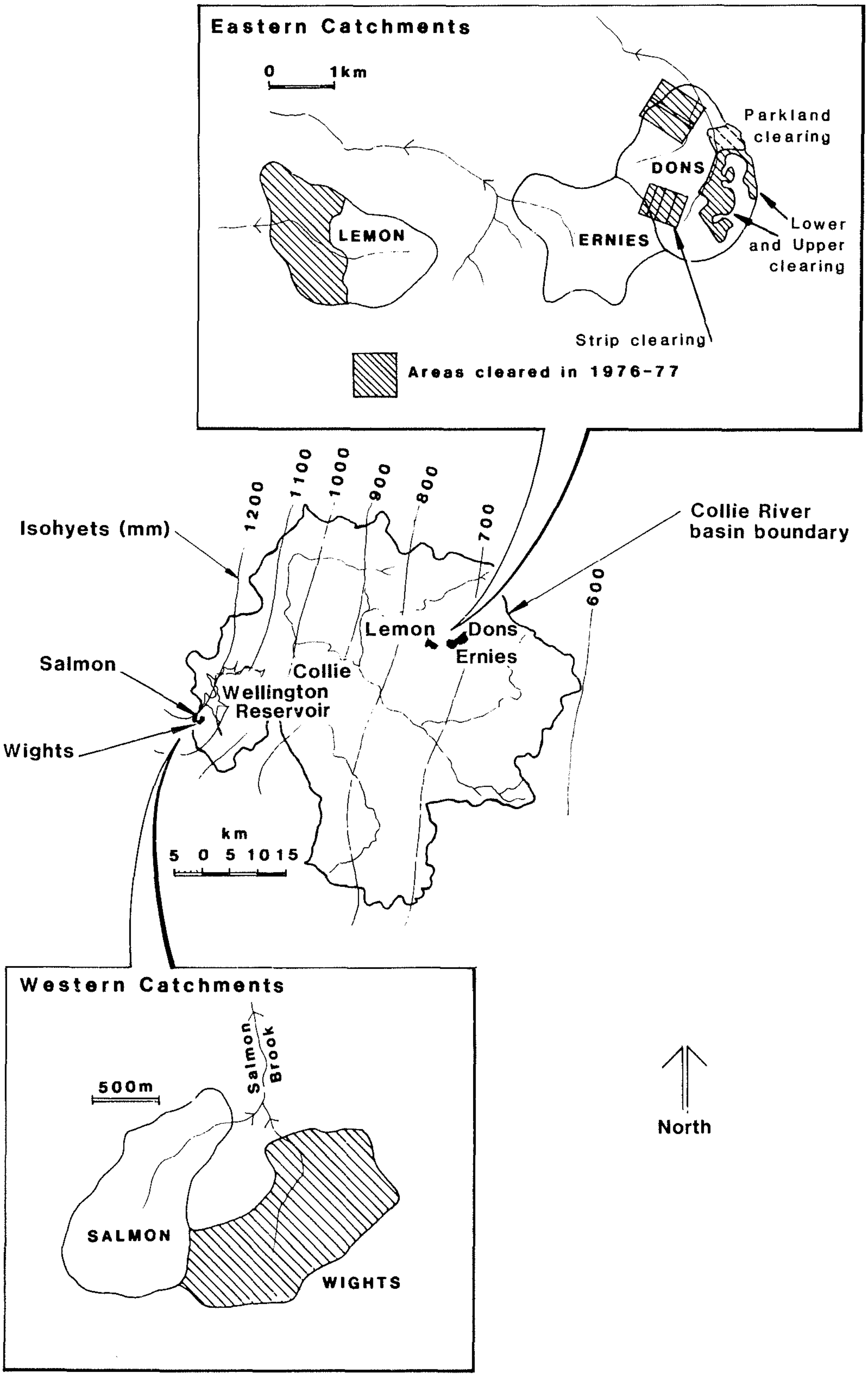


Figure 8: Clearing patterns and locations of Collie experimental catchments

Williamson *et al.* (1987) calculated a reduction in evapotranspiration of 15% of rainfall following agricultural development of Wights catchment, based on predicted and observed catchment water balance differences.

### 5.1.3 Soil water content

Increased net precipitation and decreased transpiration is likely to increase soil water content. This situation was observed on Wights and Lemon catchments following agricultural development (Sharma *et al.*, 1987). On Wights catchment (~1120 mm/yr rainfall) summer minimum soil water storage to six metres depth increased by 220 mm in the first year and a further 58 mm in the second year following clearing. Most of this increase occurred below 2 metres. For Lemon catchment (~820 mm/yr rainfall) the increase was less than 50 mm in the first year following clearing.

### 5.1.4 Groundwater

Changes to the groundwater system following the clearing treatments on Wights, Lemon and Dons catchments have been analysed by Sharma *et al.* (1982), Peck (1983), Peck and Williamson (1987), and Ruprecht and Schofield (1988). In most parts of Wights catchment the groundwater system responded immediately and rapidly to clearing. At low elevations, from the year of clearing there was a steady increase in area with hydraulic head at or above the soil surface (Figure 9). At higher elevations the response in piezometric levels was delayed for up to four years but then rose rapidly for four years before levelling off below the ground surface. In contrast, groundwater levels on the adjacent forested Salmon catchment generally declined over the same period.

On the cleared area of Lemon catchment, groundwater levels also responded immediately to clearing and have continued to rise at a steady rate (as of 1988). Groundwater is also rising in the forest close to the cleared area, whereas groundwater levels have been declining deeper within the forest.

On Dons catchment the groundwater changes under the three partial clearing treatments have been very similar. All piezometers in cleared areas are showing a slow rise in groundwater level. The relative average rates of rise for cleared areas on Wights, Lemon and Dons catchments for the period 1977–81 were 1.4 m/yr, 0.7 m/yr and 0.3 m/yr.

Hookey (1987) used a two-dimensional groundwater model to carry out further investigation of the groundwater response in the Collie experimental catchments, and to examine groundwater responses to clearing across the Collie River basin. For the high rainfall Wights catchment, the model showed an immediate increase in groundwater discharge to the stream. Groundwater discharge was predicted to attain equilibrium with recharge 20 years after clearing. In contrast the lower rainfall Lemon catchment was predicted to begin discharging groundwater to the stream 12 years after clearing and would not reach equilibrium for 30 years. Had Lemon catchment been totally cleared, these times were predicted to reduce to nine and 20 years, respectively.

At equilibrium the groundwater discharge area on Wights catchment was predicted to be 24 ha or 26% of the catchment area. By arbitrarily increasing the recharge rate by 50%, it was found that the groundwater discharge area only increased marginally. This finding has consequences for land salinisation in suggesting that there would be an effective upper limit to the size of salt seeps. The question of whether or not an upper limit to land salinisation of the order of 26% would be applicable to the major agricultural areas which have much lower rainfall has not been investigated. It is probable that groundwater discharge areas, as a proportion of a catchment, would decrease with the decreasing recharge implied by lower rainfall, assuming similar aquifer properties. However, in moving inland from the Darling Scarp there is a geomorphological trend from sharply incised valleys to broader valleys with gentler slopes and large, flat valley floors. This trend would to some degree counteract the effects of lower rainfall on the area of groundwater discharge.

Groundwater investigations of lower rainfall areas have been carried out by Hookey and Loh (1985) at the Maringee Farms catchment. The catchment has a mean annual rainfall of 650 mm/yr and an area of 840 ha. It was progressively cleared for agriculture from 1925 to 1977 to a final level of 83% of the catchment. Using the groundwater model described above, it was predicted that a groundwater seepage covering 19% of the catchment would develop by the time of equilibrium between recharge and discharge, around 2040. The model predictions were sensitive to the aquifer parameters used, in particular the saturated hydraulic conductivity.

The effects of percentage of area cleared on groundwater discharge were assessed by modelling different clearing scenarios for Lemon catchment (Hookey, 1987). The model predicts that groundwater would not discharge for at least 30 years with clearing of less than 30% of the catchment. This level of clearing was typical of many agricultural areas before 1950. The model simulations show, however, that groundwaters would have risen substantially with this early clearing. The subsequent extensive clearing which took place since the 1950s then brought about a rapid increase in groundwater discharge and stream salinity. In many catchments in the south-west, it was not until this upslope clearing took place in the 1960s that rapid increases in stream salinity were observed.

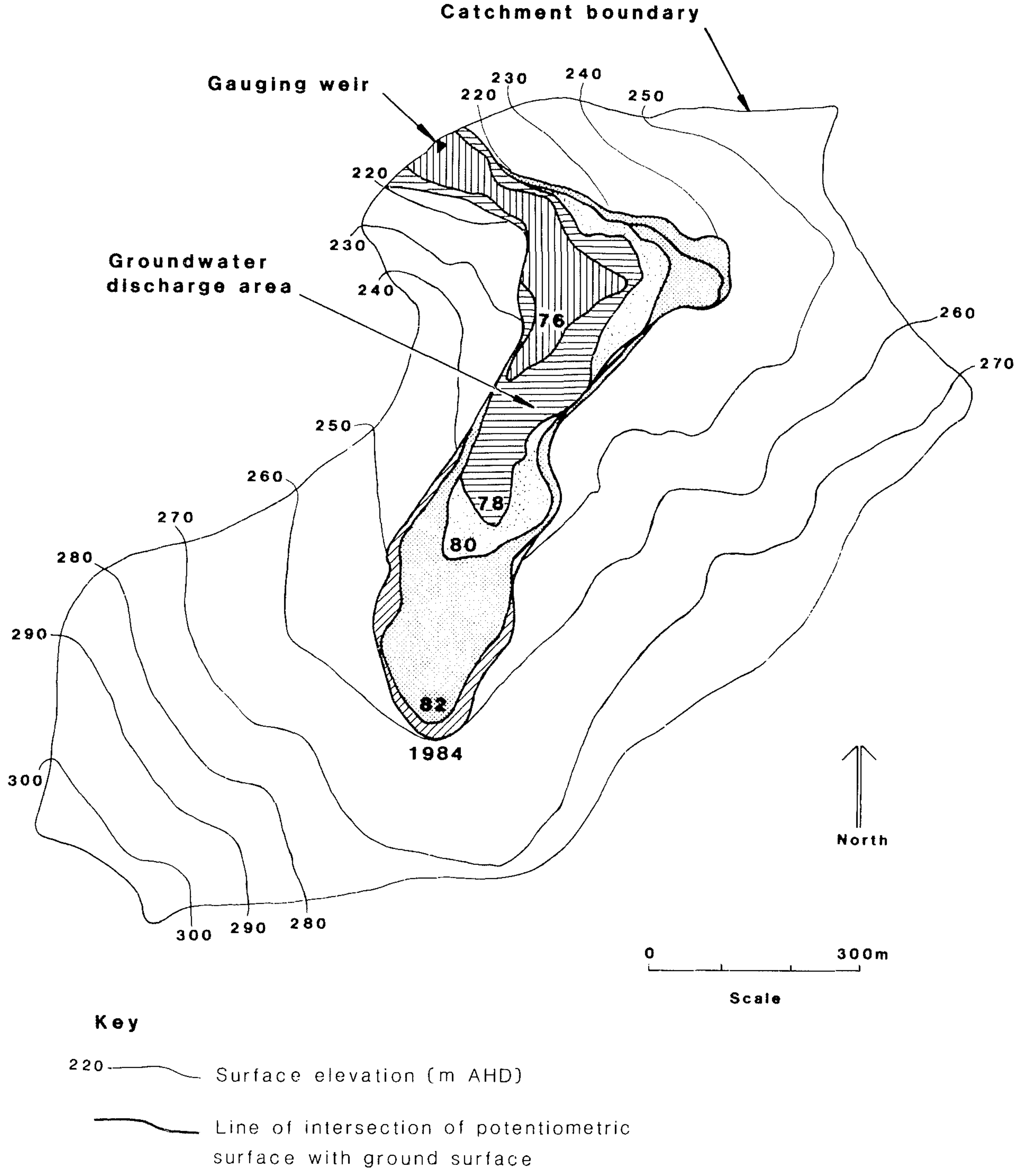


**Figure 9:**
**Growth of groundwater discharge area for Wights catchment** (after Ruprecht and Schofield, 1988)

### 5.1.5 Streamflow

Agricultural development of Wights catchment resulted in a fourfold increase in streamflow averaged over ten years since clearing. This increase was attributed primarily to decreases in transpiration and interception loss. Ruprecht and Schofield (1988) suggested that the nature of the streamflow increase following clearing was controlled largely by the expanding permanent groundwater discharge area. By 1983 the groundwater discharge area had expanded to about 18% of the catchment area (Figure 9). It was proposed that this in turn would significantly increase throughflow and overland flow. The proportions of streamflow components for Wights and Salmon catchments for 1983 are shown in Table 6. Note that throughflow here refers to lateral water movement in the shallow, permeable surface aquifer.

Table 6: Comparison of streamflow components for Wights and Salmon catchments (after Williamson *et al.*, 1987)

| | Wights (cleared) | Salmon (forest) |
|---|---|---|
| Direct runoff | 16% | 4% |
| Throughflow | 77% | 90% |
| Groundwater discharge | 7% | 6% |

It is clear that, although the proportions of groundwater discharge and direct runoff are likely to increase following clearing, throughflow remains the major streamflow component.

Partial clearing of Lemon and Dons catchments resulted in a doubling of total streamflow and direct runoff (Williamson *et al.*, 1987). The proportion of direct runoff did not increase. Further streamflow increases are likely to occur when the permanent groundwater rises to the soil surface.

To determine whether the substantial streamflow increases observed for Wights catchment also occur at the larger scale and at lower rainfalls, catchments of similar area, location and rainfall but with minor and major clearing were compared. The catchment characteristics and streamflow responses are detailed in Table 7 and Figure 10. These data suggest that the fourfold increase in streamflow on Wights can also occur for larger catchments and lower rainfalls, in response to about 50% clearing in these cases.

Table 7: Comparison of streamflows of catchments with minor and major clearing

| Catchment | NGSN* | Annual rainfall (mm) | Area (km²) | Area cleared (%) | Average annual streamflow (1975-82) (mm) |
|---|---|---|---|---|---|
| Canning R. | 616065 | 890 | 544 | 0 | 16 |
| Wooroloo Bk. | 616001 | 850 | 536 | 50 | 75 |
| Bingham R. | 612014 | 780 | 392 | <10 | 9 |
| Collie R. | 612230 | 650 | 169 | 60 | 29 |

*National Gauging Station Number

## 5.2 Salinity Changes

### 5.2.1 Salt precipitation

Although it has been recognised for some time that saltfall is enhanced beneath vegetation, there have been few data published in Western Australia. Williamson *et al.* (1987) found that salt deposition was enhanced by 0–100% under jarrah vegetation compared to values in cleared areas or in canopy openings. They concluded that the enhancement was due to salt extraction from the soil by vegetation, which exuded salt at the leaf surface to be washed back to the ground. Since this process is cyclic, it is not expected that net salt input under native forest and cleared conditions would be significantly different.

### 5.2.2 Soil salt content

There is strong evidence that catchments cleared for agriculture export salt at considerably higher rates than salt is input (Peck and Hurle, 1973), causing a net reduction in catchment salt storage. To date there have been no attempts to detect changes in soil salt storage following clearing because the annual loss is usually such a small percentage of total salt storage. Also there would be sampling problems due to the high spatial variability of soil salt content. Knowledge of the change in salt distribution within a catchment over time, following clearing, would be useful to techniques or models aiming to predict the long-term salinity behaviour of catchments.

### 5.2.3 Groundwater salinities

Variation of groundwater salinities with respect to rainfall for a number of cleared and undisturbed sites was considered in section 4.2.7 (Figure 7).

Groundwater salinities are clearly elevated under areas cleared for agriculture, at least where rainfall is below 900 mm/yr. The elevated groundwater salinity has been caused by groundwater rising into higher salt content parts of the soil profile.

Temporal changes in chloride concentration on the Collie experimental catchments were examined by Peck and Williamson (1987). On Wights cleared, high rainfall catchment, over the period 1974–83, 16 piezometers showed increasing salinity, five decreasing, four variable with no trend and five had no change. At all sites on the adjacent forested Salmon catchment, chloride concentrations were variable without trend. Of 28 piezometers on Dons multi-treated, low rainfall catchment, the chloride concentrations of 21 were essentially constant, six decreased and one had a small increase. On the adjacent, partially cleared Lemon catchment, ten piezometers had constant chloride concentration, three were variable without trend, two increased and five decreased. It is notable that, six years after clearing, increased chloride concentration occurred in a much smaller proportion of piezometers in the lower rainfall eastern catchments (Dons and Lemon) than Wights catchment.

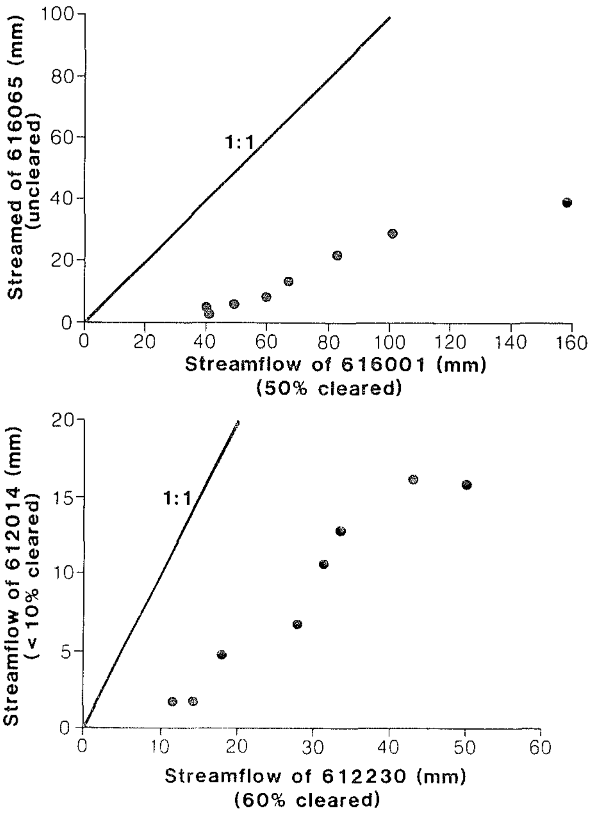


**Figure 10: Annual streamflow comparisons of catchments with minor and major clearing for period 1975–82**

### 5.2.4 Stream salinity

Stream salinity characteristics of forested catchments were discussed by Williamson and Bettenay (1979) and Loh *et al.* (1984). Broad differences in the stream salinity behaviour between catchments were attributed to whether or not groundwater contributed salts to the stream and, if so, the salinity of the groundwater. This was exemplified by comparison of seasonal stream chloride concentrations of three forested catchments: Salmon, Lewin North (in the Donnelly River basin) and Ernies (Figure 11).

Salmon catchment shows the highest and most variable stream salinity. It has a groundwater of moderate salinity (400 mg/L $Cl^-$) which discharges to the stream.

Lewin North catchment also has groundwater discharging to the stream but in this case the groundwater is of low salinity (130 mg/L $Cl^-$). Consequently the streamflow is of lower salinity. Since the salinity of groundwater is only 2–3 times greater than runoff in this catchment, the stream salinity is also somewhat less variable than Salmon, where groundwater salinity is an order of magnitude larger than runoff salinity.

Ernies catchment has a groundwater of relatively high salinity (~1000 mg/L $Cl^-$) but it lies some 15 metres below the stream bed and consequently does not discharge to the stream. As a result streamflow from this catchment has the lowest salinity and is the least variable.

The mechanisms involved in the contribution of salt to streams have not been fully elucidated. It is well known that groundwaters which lie at or near the soil surface can deposit significant amounts of salt in the surface layers during summer. The salt moves upward in solution under a capillary potential gradient driven by evaporation at the surface and/or by the groundwater hydraulic pressure head gradient. One hypothesis to explain the seasonal variability of Salmon stream salinity shown in Figure 11 is that, early in the flow season, salt is leached from the surface soils in which salt accumulates during summer by evapotranspiration of groundwater. The lower salinities during the main flow period indicate that the deposited salt has been substantially leached. Towards the end of the flow season, when flows are decreasing, groundwater discharge becomes an increasing proportion of the flow and dominates the streamflow salinity. A second hypothesis to account for the Salmon stream salinity variation is that the first flow in autumn is groundwater, hence giving a stream salinity concentration close to that observed for the groundwater. This mechanism has been observed on Wights catchment in April despite absence of rain (D. R. Williamson personal communication, 1988). As the initial winter rains occur, dilution of stream salinity would increase with increasing contribution of throughflow and overland flow.

There is ample evidence for increased stream salinity following agricultural clearing although there have been few controlled experiments to demonstrate this behaviour. Clearing of the experimental Wights catchment resulted in a five-fold increase in stream salt load, a fourfold increase in streamflow and an increase in stream salinity of order 220 mg/L TSS (Williamson *et al.*, 1987). This increase in stream salinity and total salt export following clearing was verified in a statistical sense by Macpherson and Peck (1987). Increases in stream salt load occurred on the partially cleared Lemon and Dons catchments but there has been little change in stream salinity because groundwaters have not reached a level where they could affect stream salinity.

Stream salinity levels following agricultural clearing depend on the degree to which groundwater salt discharge is diluted by increased throughflow and overland flow. In most instances in the south-west the dilution effect is not sufficient to offset the increased salt discharge.

### 5.2.5 Catchment salt balances and leaching times

Chloride input (atmospheric) to output (streamflow) ratios have been calculated for a range of forested and cleared catchments in investigations of catchment chloride balances. Peck and Hurle (1973) found that the output to input (O/I) ratios of forested catchments were in the range 1.1–1.6, while for the cleared catchments the ratios were 3.1–21. Loh *et al.* (1984) examined forested catchments over a wider range of rainfall and found a distinct trend of decreasing O/I chloride ratio with decreasing rainfall. The O/I ratios ranged from 2.1 in a 1300 mm/yr rainfall catchment to 0.17 in a 740 mm/yr catchment. The clear implication is that, during the period considered, forested catchments in high rainfall areas were undergoing a small net loss of salt while, in lower rainfall areas, forested catchments were accumulating salt. However, following agricultural clearing, salt output exceeded salt input by an order of magnitude. Similarly in small catchments in a 600 mm rainfall region, Williamson and Bettenay (1979) found increases in stream salt load followed the rising of the groundwater potentiometric surface to, or above the soil surface, and that the salt O/I ratio increased to exceed unity.

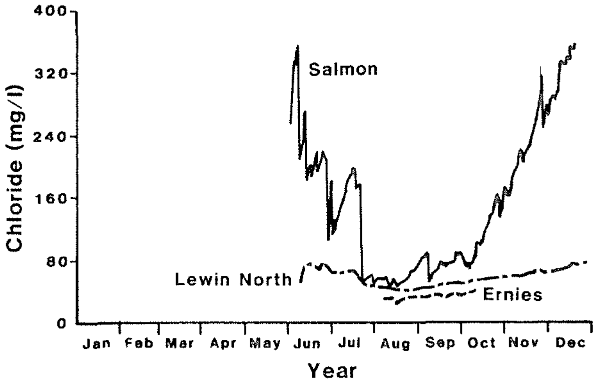


**Figure 11: Seasonal stream chloride concentrations for three forested catchments with different groundwater contributions** (after Loh *et al.*, 1984)

The high O/I salt ratios of agricultural catchments means that, ultimately, soil salt will be leached from the catchments and stream salinity will decrease to levels consistent with purely atmospheric solute input. Characteristic leaching times for some agricultural catchments were calculated by Peck and Hurle (1973) on the basis of Eriksson's (1960) definition that the characteristic equilibration time is the ratio of the amount of groundwater stored to the rate of groundwater discharge. The characteristic leaching times ranged from 30 years (1120 mm/yr rainfall) to 400 years (490 mm/yr rainfall).

Williamson *et al.* (1987) used the same approach as Peck and Hurle (1973) to determine the characteristic leaching times of Wights catchment at 30 years. They also calculated the time to export the salt content of the catchment prior to clearing (4 x $10^6$ kg Cl) at a uniform rate of 86 x $10^3$ kg $Cl^-$/yr (1981-83 average) as about 50 years. Macpherson and Peck (1987) obtained two estimates of the time to chloride equilibrium using a 'lumped piston flow model' and a 'lumped kinetic model'. In the former model the equilibration time was 60 ± 49 years and in the second model the catchment excess salt output was predicted to reach 87% of its final value after 90 years. Both of these estimates imply significantly longer times than those given by the Peck and Hurle (1973) approach.

# *6. The Regional Impact of Agricultural Development on Stream Salinity*

## 6.1 Regional Analysis

The controlled small catchment experiments described in Section 5 give a clear indication of the mechanisms and timing involved in stream salinity changes following agricultural development. Evidence of these effects at the regional scale can be obtained from the data of gauged catchments. Streamflow and stream salinity data for all gauged catchments to 1982 have been reported by the Public Works Department of W.A. (1984). As a significant number of gauging stations either lie on the same river or same tributary, selection criteria were established to avoid 'double-counting' in the analysis. The data set was divided into four groups:

I MAJOR RIVERS: river systems which also have gauged tributaries—represented by the principal gauging station of the system;

II TRIBUTARIES AND MINOR RIVERS: tributaries of major rivers—represented by the principal gauging station of tributary—and minor rivers which have no gauged tributaries;

III COASTAL RIVERS: small rivers draining directly to the ocean

IV RESEARCH STREAMS: small streams whose catchments are relatively undisturbed over the period of record analysed (minimum area 0.5 km$^2$).

The catchments within each group and their relevant characteristics are given in Appendix A.

## 6.2 Regional Effects of Agricultural Clearing on Stream Salinity in Different Rainfall Zones

Annual flow-weighted mean stream salinities of Group II and IV streams are given as a function of catchment average rainfall and percentage land cleared in Table 8. Stream salinities are fresh in all rainfall classes where there has been no clearing. The effect of clearing in areas above 1100 mm/yr rainfall is to marginally increase stream salinity but with average salinities remaining well in the fresh range. The average effect of clearing is to

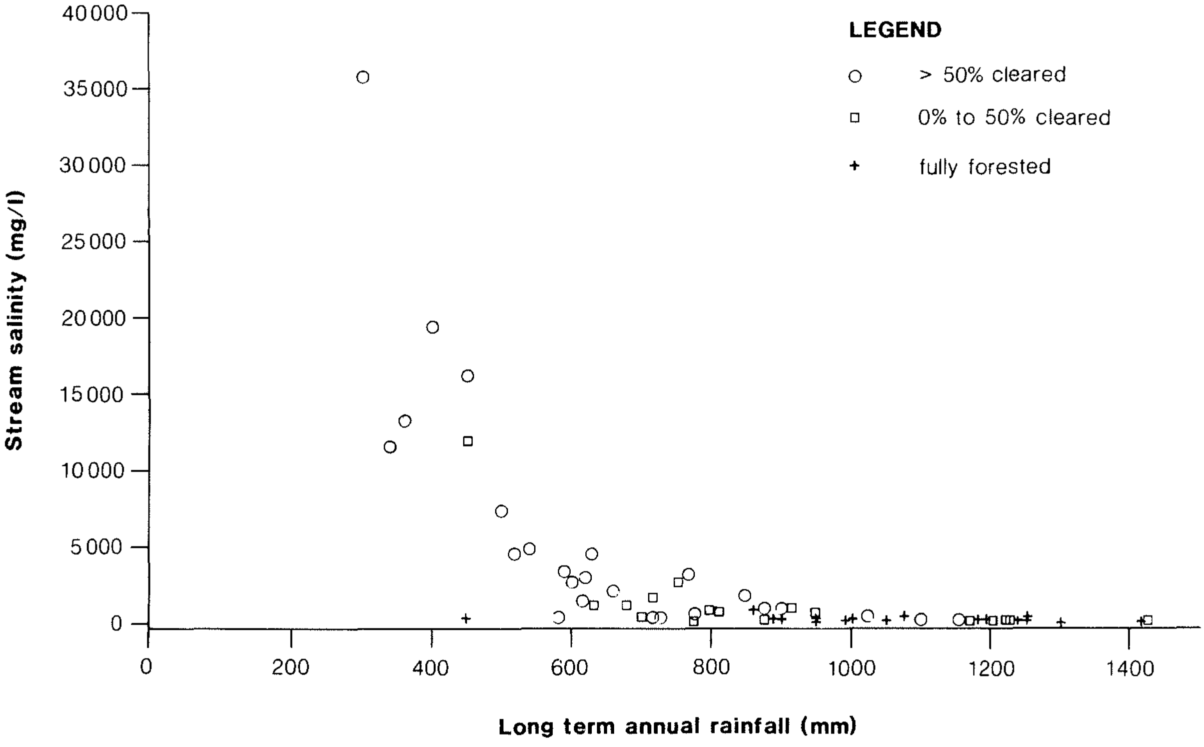


Figure 12: Relationship between average annual stream salinity and catchment average rainfall

raise stream salinities from fresh to marginal in the 900–1100 mm/yr rainfall zone; to marginal or brackish in the 700–900 mm/yr rainfall zone; and to brackish in the 500–700 mm/yr rainfall zone. There were no uncleared catchments in the data set below 500 mm/yr rainfall but the streams were highly saline in catchments with clearing.

The relationship between stream salinity and average rainfall is shown in Figure 12 for catchment Groups II and IV. Salinities are in the fresh category above 1000 mm/yr rainfall, vary up to 5000 mg/L from 500–1000 mm/yr rainfall and increase rapidly to very high values below 500 mm/yr rainfall.

**Table 8:**
**The regional effects of agricultural clearing on stream salinity in annual rainfall classes**
(Stream salinity measurements in mg/L, averaged for the numbers of catchments shown in brackets.)

| **annual rainfall** (mm) | **percentage of catchment cleared** **0** | **0–50** | **50–100** |
|---|---|---|---|
| <1100 | 144 (17) | 176 (14) | 233 (2) |
| 900–1100 | 260 (13) | 500 (4) | 697 (2) |
| 700–900 | 386 (5) | 1095 (5) | 756 (4) |
| 500–700 | 70 (1) | 1272 (1) | 3488 (10) |
| < 500 | - | 11988 (1) | 19255 (5) |

## 6.3 Effects of Area Cleared on Stream Salinity

Increasing stream salinity with increase in the proportion of catchment cleared is evident for most of the rainfall zones considered in Table 8. The exception is the 700–900 mm/yr rainfall zone which apparently has the reverse trend. Three of the four catchments in the 50–100% clearing category in this rainfall zone have anomalously low stream salinities. The lower stream salinities are probably associated with these catchments being located outside the jarrah forest (to the north-west) on soils dissimilar to the Darling Range.

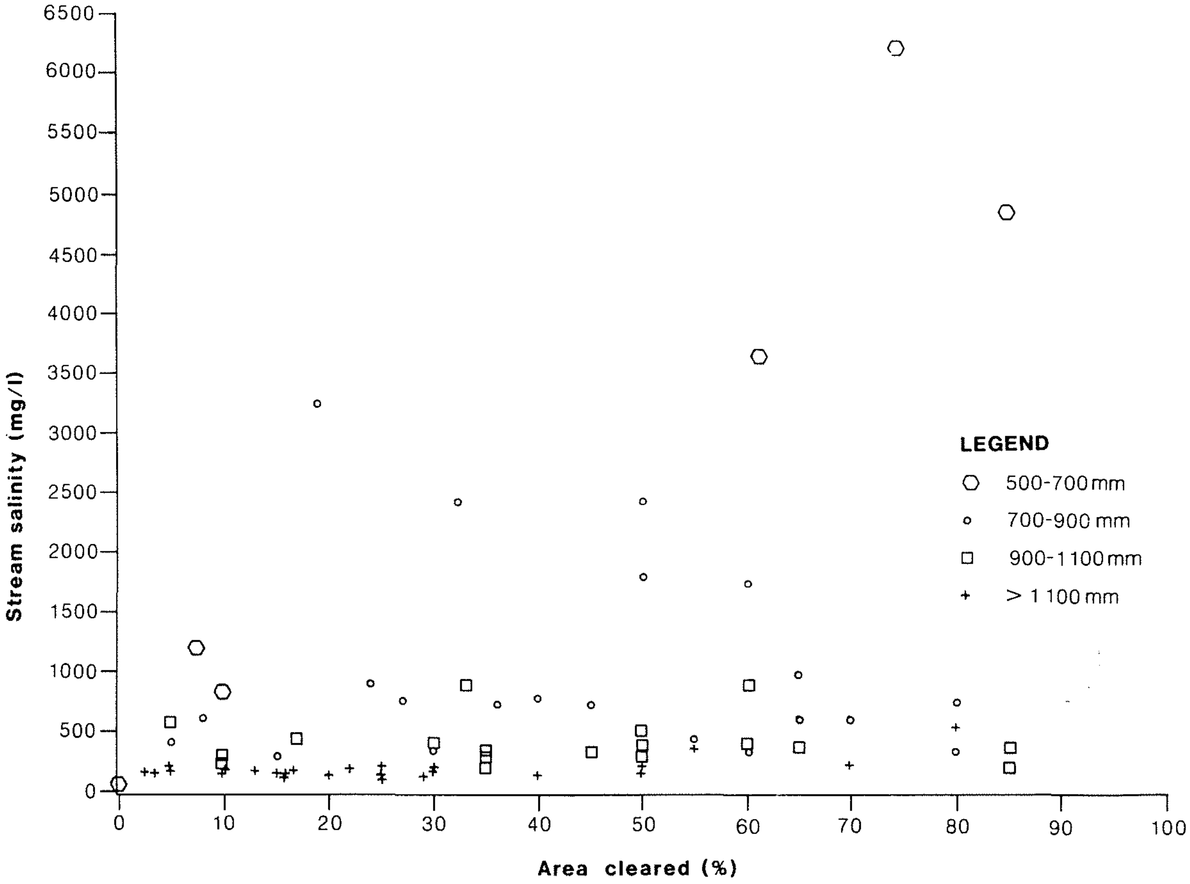


Figure 13: **Relationship between mean stream salinity and proportion of catchment cleared for four rainfall zones**

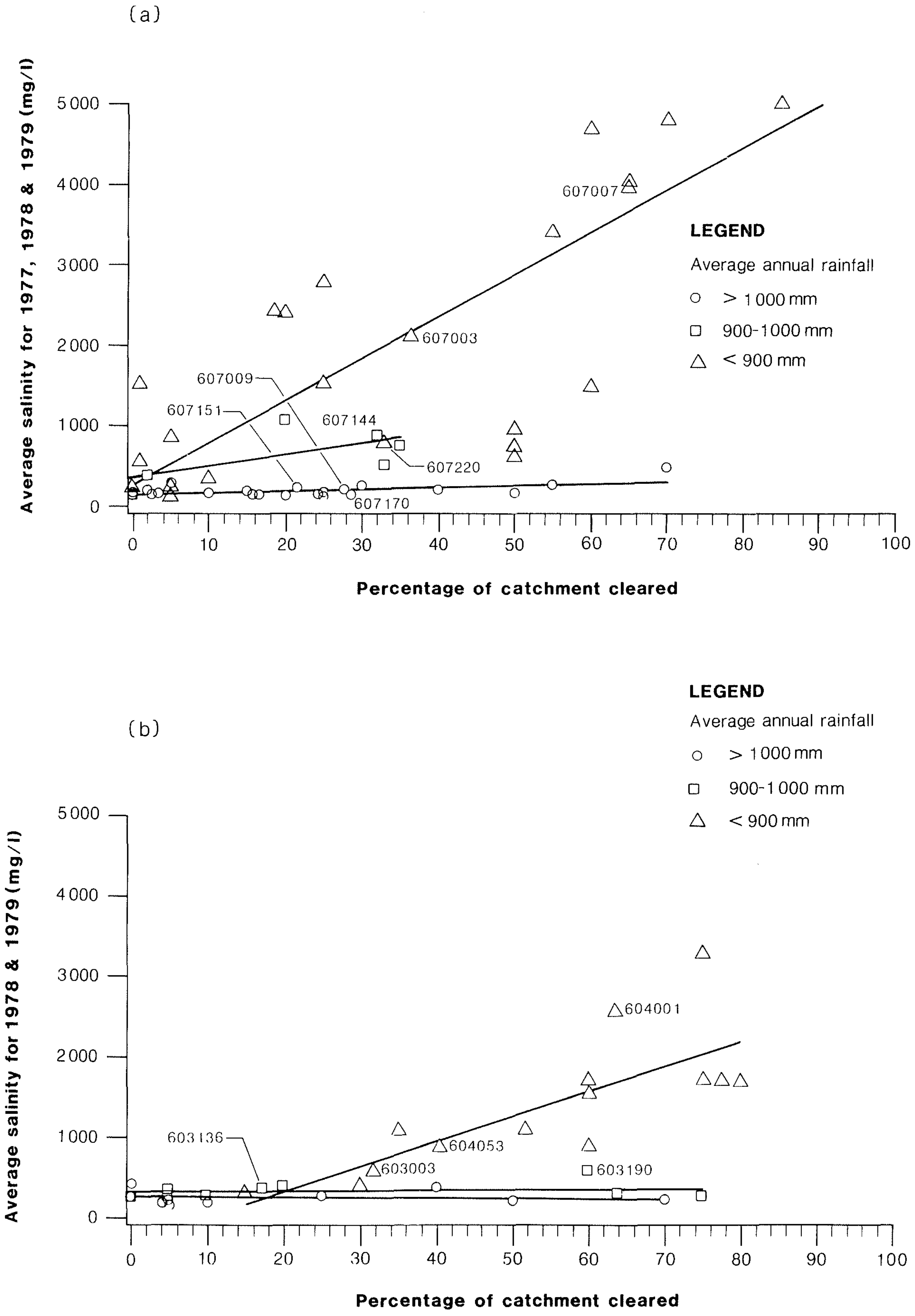


**Figure 14: Stream salinity versus area cleared for subcatchments of (a) Shannon, Warren, and Donnelly Rivers and (b) Kent, Denmark and Hay Rivers**

Table 8 also indicates that the degree to which salinity rises with agricultural development depends on a combination of clearing and rainfall zone (i.e. salt storage). Extensive clearing in the high rainfall zone will have little effect, whereas a small amount of clearing below 900 mm/yr rainfall may cause a significant stream salinity increase. These relationships are clear from Figure 13, in which average annual flow-weighted stream salinity is graphed against percentage of catchment cleared for Group II catchments.

The best representation of the effect of the proportion of area cleared on stream salinity was given by Collins and Barrett (1980) and Collins and Fowlie (1981). Their salinity versus area data for the Shannon-Warren-Donnelly catchment group and the Kent-Denmark-Hay group have been represented as linear regressions in Figures 14a and b respectively. Stream salinity data were collected on a large number of subcatchments within these catchment groups over the period 1977–79. A similar salinity versus area relationship is apparent for both catchment groups, although the Shannon-Warren-Donnelly group shows higher rates of salinity increase with increasing area than the Kent-Denmark-Hay group for all rainfall zones. For both groups the percentage of area cleared only has a slight effect on stream salinity above 1000 mm/yr rainfall, with stream salinities remaining fresh even at high percentage clearing. In the 900–1000 mm/yr rainfall range, the rate of salinity increase with area cleared is significant for the Shannon-Warren-Donnelly group, with stream salinities becoming marginal above about 10% clearing. For the Denmark-Kent-Hay group, percentage area cleared had little impact on stream salinity in this rainfall range. Below 900 mm/yr rainfall, the rate of stream salinity increase with area cleared was high for both catchment groups.

# 7. *Time Trends in Stream Salinity*

## 7.1 Introduction

This section deals with time trends of stream salinity over periods in which records have been gathered. There are usually few catchments with long periods of record for any particular set of conditions, and general statements or conclusions should be treated with a degree of caution. It is largely assumed in this section that trends of increasing salinity are due to agricultural clearing, evidence for which has been described in previous sections. Some minor trends in stream salinity may occur as a result of climate fluctuations, such as several years of lower or higher than average rainfall, or from changes in forest cover due to logging, wildfires, disease etc..

Five-year moving average annual flow-weighted mean salinities have been considered adequate to illustrate trends, and simple linear regressions on the unsmoothed annual salinity data have been used to calculate rates of salinity change. Time trend analyses based on salinities corrected to median flow years were briefly reported by Loh *et al.* (1983).

## 7.2 Salinity Trends of Uncleared Catchments

Climate and other factors not associated with agricultural development can affect salinity trends of fully forested catchments. Examples of such salinity trends for high, intermediate and low rainfall zones are shown in Figure 15.

The North Dandalup River (1300 mm/yr rainfall) has a period of record from 1939–86. Over this time the stream has been fresh with relatively low annual salinity variability (mean = 185 mg/L, standard deviation S.D. = 36 mg/L, coefficient of variation C.V. = 19%). There has been a marked downward trend in stream salinity of 1.5 mg/L/yr over the period 1939–86 which is significant at the 0.01% level. The rate of decrease in annual salinity has accelerated in recent times, averaging 7.4 mg/L/yr over the period 1976–86.

Yarragil Brook catchment (1050 mm/yr rainfall) has the longest record (1951–86) of all intermediate rainfall zone catchments. Its stream salinity is higher and more variable than the high rainfall zone catchment (mean = 389 mg/L, S.D. = 120 mg/L, C.V. = 31%). Stream salinity in this catchment has declined at an average rate of 7.7 mg/L/yr over the period of record and has a current (1976–86) rate of decrease of 16 mg/L/yr.

In lower rainfall areas there are very few fully forested catchments. The Canning River (station 616065), with the longest period of record (1968–86), has a mean stream salinity of 293 mg/L (S.D. = 132 mg/L, C.V. = 45%). The average rate of decline in stream salinity over the whole period was 17 mg/L/yr while its rate of decline over the period 1976–86 was 13 mg/L/yr.

It is evident that significant stream salinity reductions have been occurring on forested catchments over the last 20 years or so. The main reason for this is considered to be the general decline in groundwater level in response to generally lower rainfall conditions. A clear example of this is shown in Figure 16 for Bee Farm Road catchment, where groundwater close to the gauging station fell 4.4 m from 1976 to 1981. Over the same period the annual stream salinity declined at an average rate of 128 mg/L/yr. The rainfall for the period was 10% below the long term average. The decline in groundwater would mean a decrease in salt contribution to streams both directly as groundwater flow and indirectly as salt movement to the surface soil layers during summer and subsequent leaching to streams during winter.

The salinity trends of all forested catchments are shown in Table 9. All but two of these catchments show declining stream salinities, but the trends are only statistically significant for half of the catchments, for the total record period, at the 1% level.

## 7.3 Salinity Trends of Catchments with Agricultural Clearing

Agricultural clearing almost invariably results in increased stream salinity in the south-west. However, the degree of increase is highly variable between catchments, depending on such factors as annual rainfall, salt storage, groundwater hydrology, proportion of catchment cleared and clearing history. Stream salinity changes also vary over time. From the analysis of Macpherson and Peck (1987) for Wights catchment, stream salinities can be expected to increase for at least eight years after clearing (the limit of the analysis) in high rainfall areas before decreasing to a new equilibrium in about 60 years. In lower rainfall areas these periods would be substantially greater.

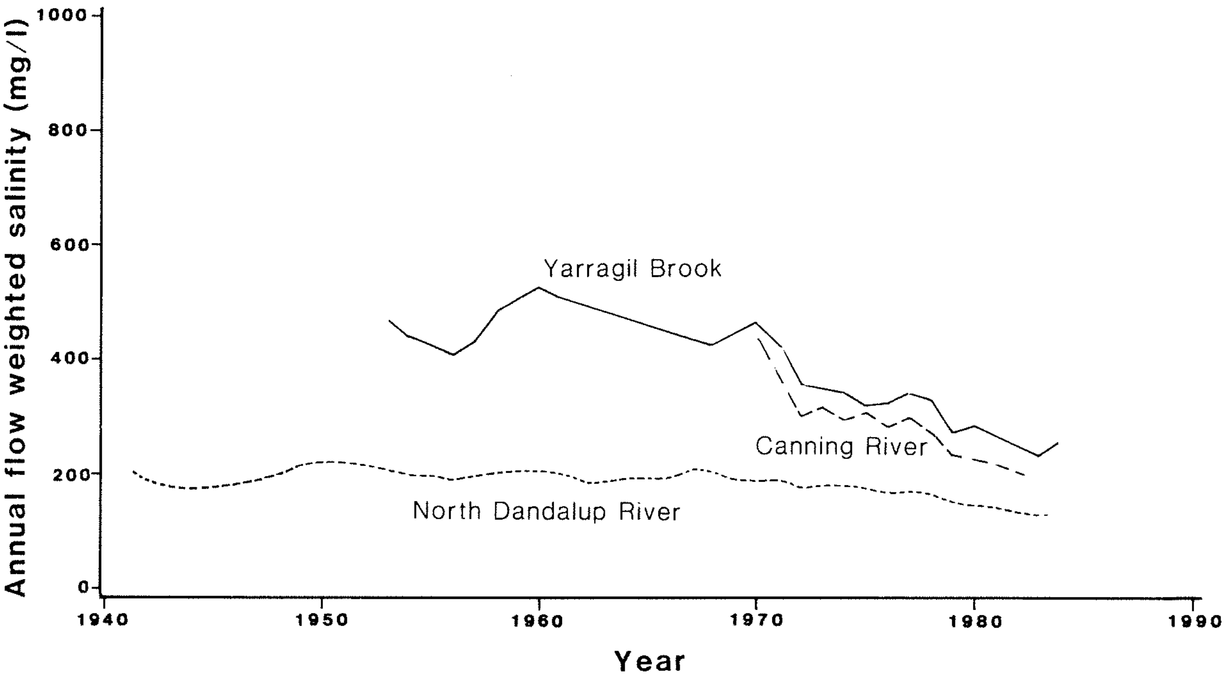


Figure 15:
Stream salinity trends for forested catchments in high, intermediate and low rainfall zones

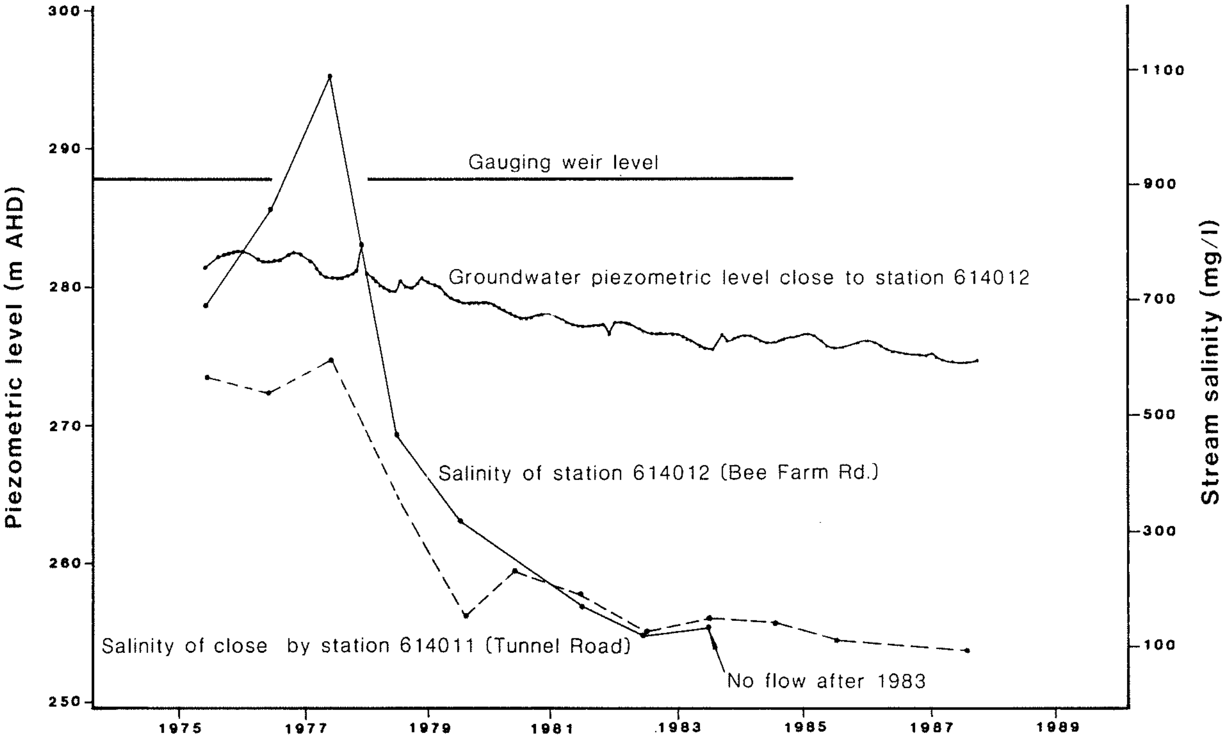


Figure 16: Response of stream salinity to decreasing groundwater levels

The effects of agricultural clearing on stream salinity trends of catchments in different rainfall zones of the Warren River catchment are shown in Figure 17. The clearing history of this catchment exemplifies the two periods of rapid agricultural expansion (Section 2) and so the behaviour of this catchment is considered representative of many in the south-west division.

**Table 9 Stream salinity trends of fully forested catchments**

| Catchment | NGSN | Area (km$^2$) | Period of record | Annual rainfall (mm) | Annual stream salinity (mg/L) | Period of record salinity trend (mg/L/yr) | Stat. sig. | Current salinity trend (1976–86) (mg/L/yr) | Stat.(1) sig. |
|---|---|---|---|---|---|---|---|---|---|
| Carey Bk | 608002 | 40.6 | 75–86 | 1420 | 116 | +0.1 | 0.78 | -0.1 | 0.69 |
| Nth Dandalup R | 614016 | 153 | 39–86 | 1300 | 185 | -1.5 | 0.0001 | -7.4 | 0.01 |
| Little Dandalup R | 614233 | 396 | 67–86 | 1300 | 138 | -3.7 | 0.0001 | -4.5 | 0.01 |
| Harvey R | 613002 | 148 | 70–86 | 1250 | 114 | -2.0 | 0.002 | -2.2 | 0.02 |
| Stones Bk | 612005 | 14.7 | 72–86 | 1220 | 181 | -0.6 | 0.86 | -3.7 | 0.44 |
| Barlee Bk | 608001/048 | 164 | 62–86 | 1170 | 152 | -0.2 | 0.82 | -2.8 | 0.42 |
| Yarragil Bk | 614044 | 72.5 | 51–86 | 1075 | 389 | -7.7 | 0.0001 | -16.3 | 0.01 |
| April Rd North | 607012 | 2.1 | 76–86 | 1070 | 122 | -1.9 | 0.19 | -1.9 | 0.19 |
| Harris R | 612036/017 | 383 | 52–86 | 1000 | 224 | -8.0 | 0.03 | -5.4 | 0.41 |
| Deep R | 606001 | 458 | 75–86 | 990 | 184 | 3.5 | 0.28 | +4.9 | 0.20 |
| Little Darkin R | 616010 | 40.1 | 67–86 | 900 | 390 | -25.9 | 0.0009 | -19.7 | 0.23 |
| Canning R (Glen Eagle) | 616065 | 544 | 68–86 | 890 | 293 | -17.0 | 0.0004 | -12.6 | 0.11 |
| Pickering Bk | 616009 | 31.1 | 74–86 | 750 | 229 | 4.9 | 0.001 | -12.1 | 0.01 |
| Tunnel Rd | 614011 | 2.07 | 75–86 | 730 | 285 | -52 | 0.001 | -47.2 | 0.003 |
| Bee Farm Rd | 614012 | 1.81 | 75–86 | 730 | 480 | -106 | 0.008 | -128 (3) | 0.0092 |
| Chalk Bk | 614123 | 104 | 59–86 | 700 | 293 | -5.0 | 0.02 | -11.7 | 0.003 |
| Yarra Rd(2) | 616017 | 6.3 | 74–82 | 680 | 90 | -8.3 | 0.08 | -7.1 | 0.23 |

(1) Statistical significance is based on the F-test, where value denotes level of significance. For example 0.70 means that the observed trend has a 70% chance of being zero (non-existent).

(2) Current salinity trend for Yarra Rd is from 1976 to 1982 due to closure of station in mid 1983.

(3) No flow recorded from 1984 onwards

Lefroy Brook (607009) is a high rainfall zone tributary of the Warren River (average rainfall of 1220 mm/yr) which has been 30% cleared. Its stream salinity has remained virtually unchanged over the period 1951–86, and has low annual variability (mean = 178 mg/L, S.D. = 18 mg/L, C.V. = 10%).

The Wilgarup River (607144) is an intermediate rainfall zone tributary (average rainfall of 915 mm/yr) and is 33% cleared. A distinctive upward trend in the stream salinity of 52 mg/L/yr has occurred over the period of record. The annual stream salinity of this catchment is highly variable (mean = 866 mg/L, S.D. = 294 mg/L, C.V. = 34 %).

The Perup River tributary (607004) enters the upper reaches of the Warren River and has an average annual rainfall of 765 mm/yr and is 18.5% cleared. The increasing stream salinity trend on this catchment is the most dramatic, with an annual increase of 230 mg/L for the period of record (1961–86). The stream salinity of this catchment is also the most variable (mean = 2807 mg/L, S.D. = 1582 mg/L, C.V. = 56%).

This comparison supports the general picture of higher stream salinities in lower rainfall areas. The integrated effects of clearing in the Warren catchment is shown in Figure 17 for the Warren River at Barker Road Crossing (607220). The average rainfall for the whole catchment is 865

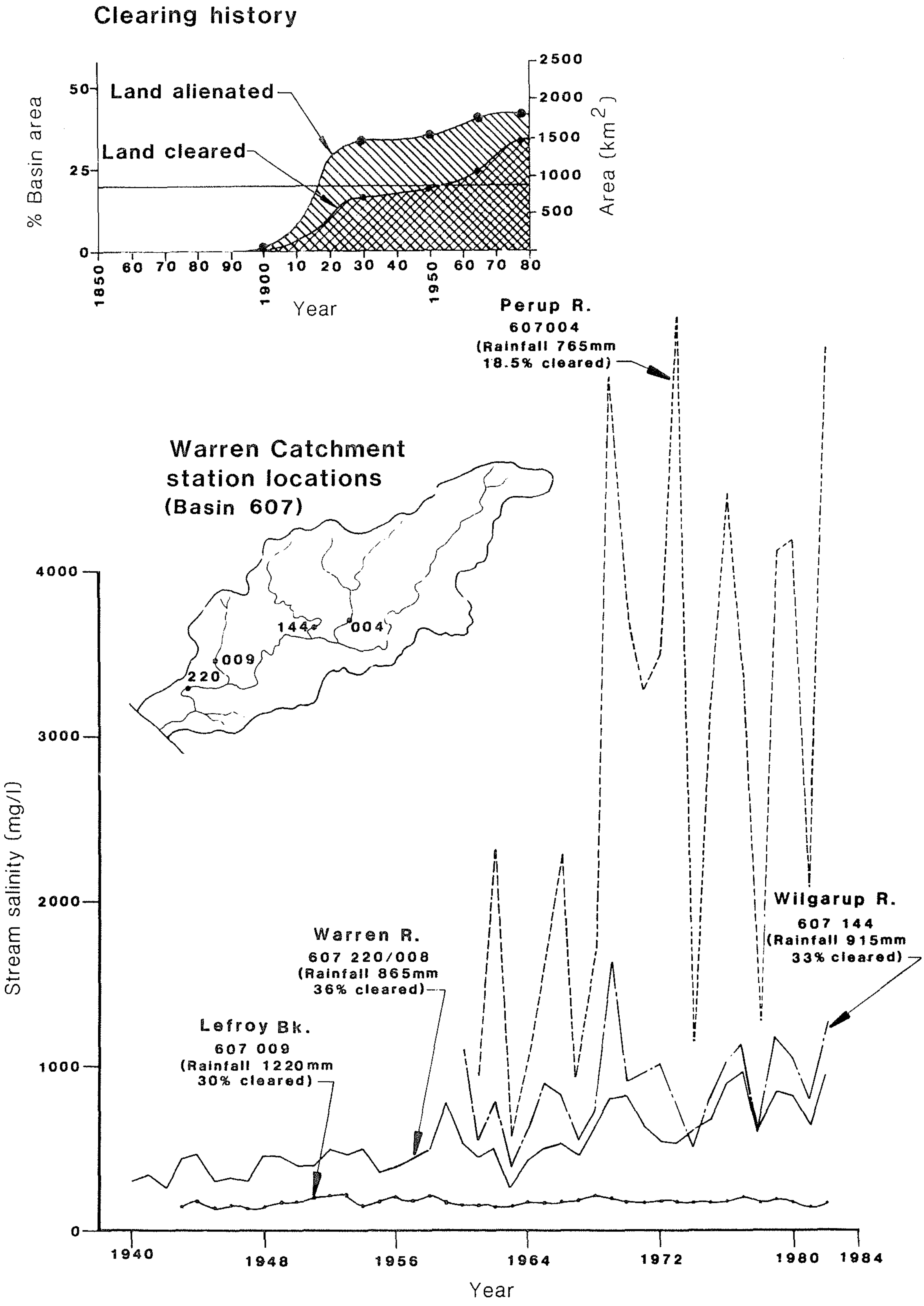


Figure 17: Stream salinity trends in response to clearing within the Warren catchment

mm/yr and it is 36% cleared. The salinity trend is clearly increasing, with an annual rate of increase of 12 mg/L. The rate of stream salinity increase rose markedly after 1955 (pre-1955: 8 mg/L/yr; post-1955: 13 mg/L/yr).

All the major catchments of the south-west division which have lower rainfall for their upper reaches and have been subjected to partial or total clearing, exhibit similarly deteriorating stream salinities.

## 7.4 Trends in Stream Salinity Characteristics

### 7.4.1 Stream salinity variability

In addition to the general trend of higher stream salinity in lower rainfall areas, the Warren catchment data (Figure 17) show that the variability of annual average stream salinity increases with decreasing rainfall in partially cleared catchments. For the Perup River there was also a trend of increasing variability in stream salinity with time as salinity increased. In general, high annual salinity variability is associated with streams of high salinity, and the time trend of increasing variability is merely a result of the increasing absolute stream salinity.

### 7.4.2 Trends in salinity-flow relationships

It has been noted frequently that the annual stream salinities of brackish and saline streams are inversely related to streamflow. In high rainfall-high runoff years, stream salinities are lowest, and the converse is true in low runoff years. In catchments with a trend of increasing annual stream salinity, this salinity-flow relationship varies over time, as demonstrated by the Frankland River (Figure 18). In this case the salinity-flow relationship has been displaced towards higher salinity and with increased slope (curves A to D in Figure 18) over time. This indicates a 'permanent' change to higher salinities and greater variability for the same flow regime.

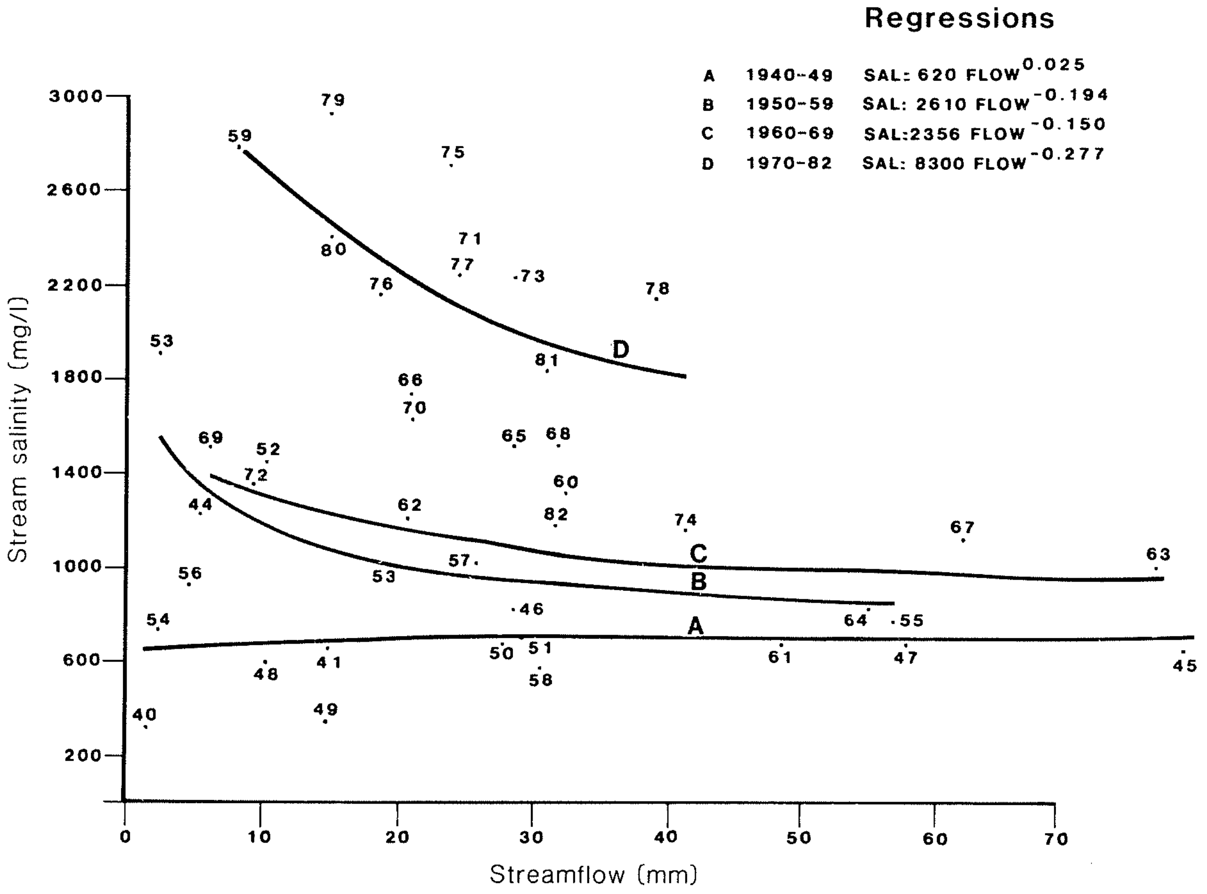


**Figure 18:**
**Changes in salinity-flow relationship in response to clearing for Frankland River (605012)**

## 7.5 Regional Salinity Trends

Rivers which show high rates of increase in stream salinity are given in Table 10. Only catchments with a period of record greater than 10 years and with salinity trends that are statistically significant at less than the 25% level have been considered. All these catchments have been partly cleared for agriculture. Tributaries have not been included with the exception of the Warren and Murray rivers. Two rivers are currently fresh (Capel and Preston) and six are marginal. Of the four catchments with periods of record greater than 40 years, the Frankland, Collie and Murray, but not the Warren have shown substantially higher rates of salinity increase since 1965.

The distribution of surface water resources in the south-west region, their current salinity and rates of salinity increase if statistically significant at the 5% level are summarised in Figure 19. This figure shows that the major rivers of the south-west are now marginal or brackish. These include the Avon R. (brackish), Murray R. (brackish), Blackwood R. (brackish), and Warren R. (marginal). Nearly all of the marginal rivers are increasing in salinity. Halting or reversing the deteriorating salinity of the important marginal resources is the major objective of water resource catchment management. These marginal resources and the high yielding fresh streams will form the main basis of future water resources development.

Table 10: Stream salinity trends of major rivers

| Catchment | NGSN | Period of record | Area cleared (%) | Average stream salinity over last 5 years of record (mg/L) | Rate of stream salinity increase over period of record (mg/L/yr) | Stat. sig. | Rate of stream salinity increase since 1965 (mg/L/yr) | Stat. Sig. |
|---|---|---|---|---|---|---|---|---|
| Denmark R | 603136 | 1960–86 | 17 | 890 | 25 | 0.0001 | 26 | 0.0001 |
| Kent R | 604053 | 1956–86 | 40 | 1870 | 52 | 0.0001 | 58 | 0.0002 |
| Frankland R | 605012 | 1940–86 | 35 | 2192 | 44 | 0.0001 | 74 | 0.004 |
| Warren R | 607220 | 1940–86 | 36 | 870 | 12 | 0.0001 | 15 | 0.0056 |
| Perup R(1) | 607004 | 1961–86 | 19 | 3410 | 132 | 0.009 | 117 | 0.067 |
| Wilgarup R(1) | 607144 | 1961–86 | 33 | 863 | 20 | 0.044 | 14 | 0.253 |
| Blackwood R | 609025 | 1956–86 | 85 | 2192 | 52 | 0.0001 | 58 | 0.002 |
| Capel R | 610129/219 | 1959–76 | 50 | 423 | 15 | 0.018 | 14 | 0.24 |
| Preston R | 611049 | 1955–75 | 50 | 354 | 8 | 0.037 | 11 | 0.352 |
| Thomson R | 611111 | 1957–85 | 45 | 534 | 18 | 0.0001 | 17 | 0.0017 |
| Collie R | 612033 | 1940–86 | 24 | 730 | 11 | 0.0001 | 24 | 0.0001 |
| Murray R | 614006 | 1939–86 | 75 | 2792 | 39 | 0.0001 | 93 | 0.005 |
| Williams R(2) | 614196 | 1966–86 | 90 | 2425 | 95 | 0.10 | 95 | 0.104 |
| Hotham R(2) | 614224 | 1966–86 | 85 | 3711 | 89 | 0.21 | 89 | 0.213 |
| Wooroloo Bk | 616001 | 1965–86 | 50 | 2092 | 44 | 0.026 | 39 | 0.069 |
| Brockman R | 616019 | 1963–86 | 65 | 2040 | 76 | 0.0002 | 72 | 0.0009 |
| Helena R | 616216 | 1966–85 | 10 | 1257 | 48 | 0.11 | 48 | 0.1105 |

(1) Tributaries of the Warren River

(2) Tributaries of the Murray River

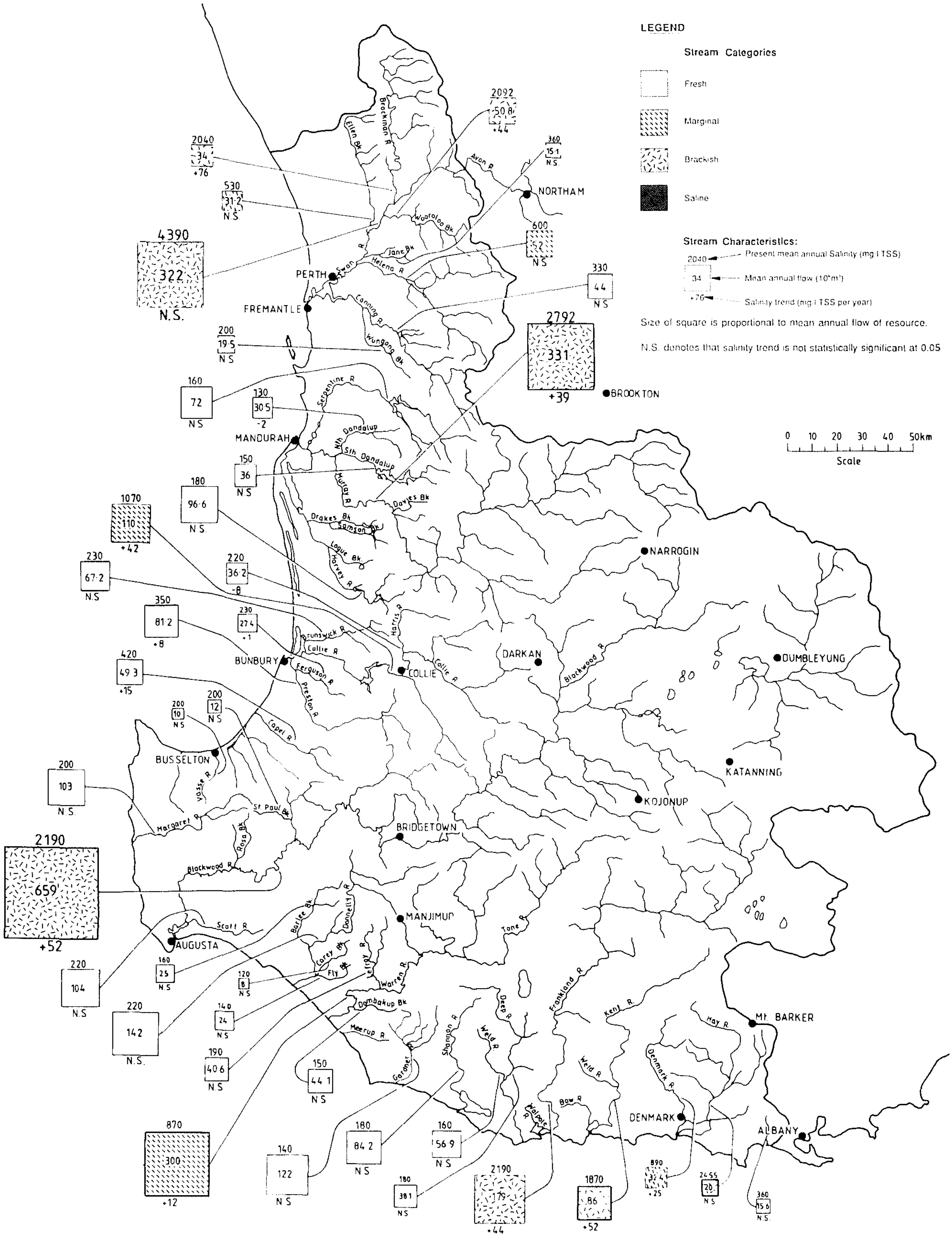


Figure 19: The distribution of surface water resources of south-west Western Australia, their salinities and rates of salinity change

# 8 *Prediction of Future Stream Salinities*

Predicting future stream salinities in catchments where there has been clearing for agriculture is important for the management of current water supplies and for the development of future water resources. The capability of predicting stream salinities for given clearing patterns has progressed in recent years but further development is still required. The problem is made difficult by the complexities of water and salt discharge mechanisms, the distribution of clearing within the catchment and the strong influence of climate fluctuations.

## 8.1 Darling Range Catchment Model

A numerical, physically-based, parametric process model, known as the Darling Range Catchment Model (DRCM) was developed for the prediction of stream salinity by the Water Authority of Western Australia (Hopkins, 1984; Mauger, 1986). The model simulates the generation of streamflow and stream salinity from data on rainfall, evaporation and physical characteristics of a catchment. The model has the ability to take account of forest clearing, reforestation and seasonal leaf area changes. Landsat satellite data are used to estimate leaf area index and crown cover.

The basic unit of the model is a subcatchment from which water and salt are routed through a stream network to the catchment outlet. The main components modelled within a subcatchment are: a shallow aquifer representing a permeable surface soil horizon over most of the catchment; a deep aquifer representing the underlying low-permeability saprolite; swamps; stream zones; and forest or agricultural vegetation. The hydrological processes include interception, transpiration, infiltration, direct runoff, drainage from aquifers and channel routing. Salt discharge is derived from atmospheric input and mobilisation of salt stored in the subsoil.

The model is generally calibrated on observed data records by intuitive manipulation of parameter values. Good fits to observed annual flows and annual mean salinities have been obtained.

DRCM has been used to predict stream salinities of three potential water supply catchments (Jane, Susannah and Ellen) which have been extensively cleared for agriculture (Hammond and Mauger, 1985a, b). Following calibration, simulations for various clearing conditions were carried out over the period of climatic record (1911–83). In each case the model parameters were initialised to match the assumed forested condition at the beginning of the simulation. The results are summarised in Table 11 and Figure 20.

The simulated change from fully forested to totally cleared conditions brought about substantial increases in streamflow on all catchments. The stream salinities of Jane and Susannah catchments increased approximately three times while

**Table 11: Stream salinity predictions by the Darling Range Catchment Model**

| | Jane | Susannah | Ellen |
|---|---|---|---|
| Area (km$^2$) | 74 | 27 | 540 |
| Area cleared (%) | 61 | 65 | 59 |
| Mean annual rainfall range (mm) | 1000–1050 | 950–1000 | 660–820 |
| Stream monitoring period | 1963–83 | 1981–83 | 1965–83 |
| Average annual flow-weighted salinity over monitored period (mg/L) | 415 | 358 | 689 |
| Predicted fully-forested salinity (mg/L) | 156 | 146 | 330 |
| Predicted fully-cleared salinity (mg/L) | 433 | 444 | 380 |
| Predicted salinity at current clearing level (mg/L) | 449 | 401 | 630 |
| Predicted fully-forested flow (10$^6$m$^3$) | 7.9 | 3.1 | 20 |
| Predicted fully-cleared flow (10$^6$m$^3$) | 27.2 | 8.1 | 130 |
| Predicted soil salt accumulation time (yr) | 1300 | 2400 | 4300 |
| Predicted time to leach all soil salt under total clearing (yr) | 74 | 88 | 84 |

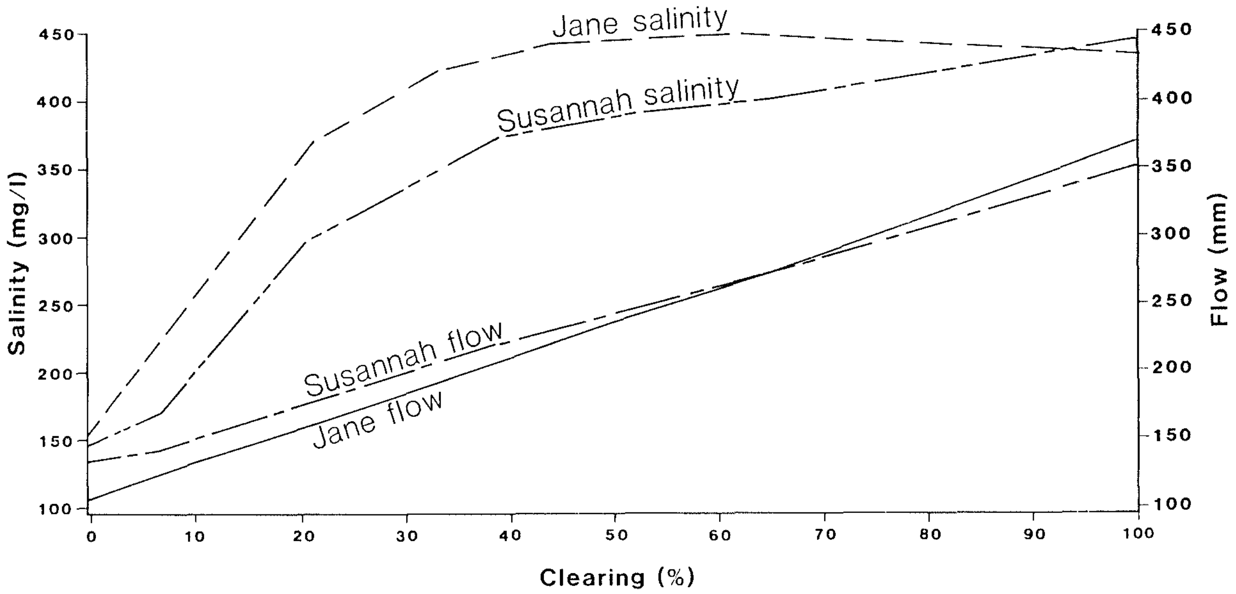


**Figure 20:**
**Predicted effects of clearing on streamflow and salinity for Jane and Susannah catchments**

there was only a marginal increase predicted for Ellen Brook. The small change for Ellen Brook is because only 20% of the catchment contains significant soil salt storage. However, since most of the high salt content area and only part of the low salt content area have been cleared, the current stream salinities are considerably higher than would be the case for full clearing.

The predicted effects of percentage of area cleared on stream salinity are shown for Jane and Susannah catchments in Figure 20. Streamflow increased approximately uniformly with clearing percentage whereas stream salinity increased rapidly for the first 20–30% of clearing but then levelled-off or decreased slightly (e.g. Jane catchment) at higher percentage clearing. For a fixed percentage clearing, variation of the distribution of clearing between subcatchments did not significantly affect the stream salinity. For Jane and Susannah catchments the annual flow-weighted stream salinity was predicted to exceed 600 mg/L in 10% of years under total clearing, and Ellen Brook, under the 1981 clearing pattern, would exceed 750 mg/L in 30% of years.

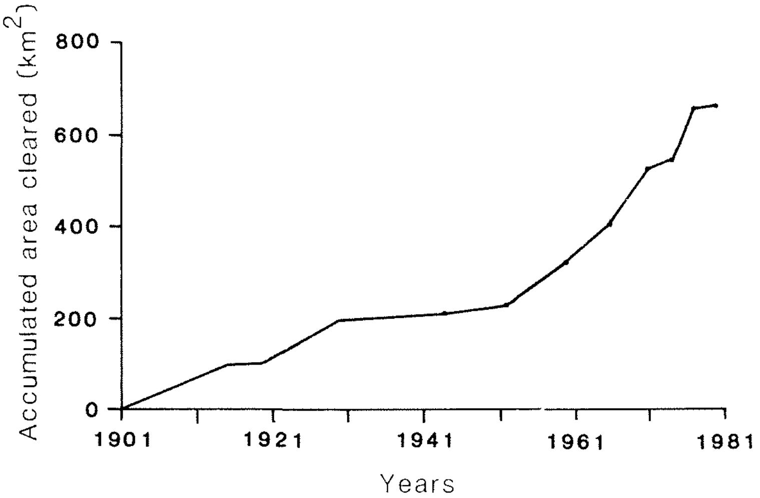
## 8.2 Loh and Stokes Model

Loh and Stokes (1981) developed an empirical model to predict the future impacts of past agricultural development on annual salinity and flows into the Wellington Dam. The model has also been used to predict future salinities of some important marginal water resources (see section 9.4).

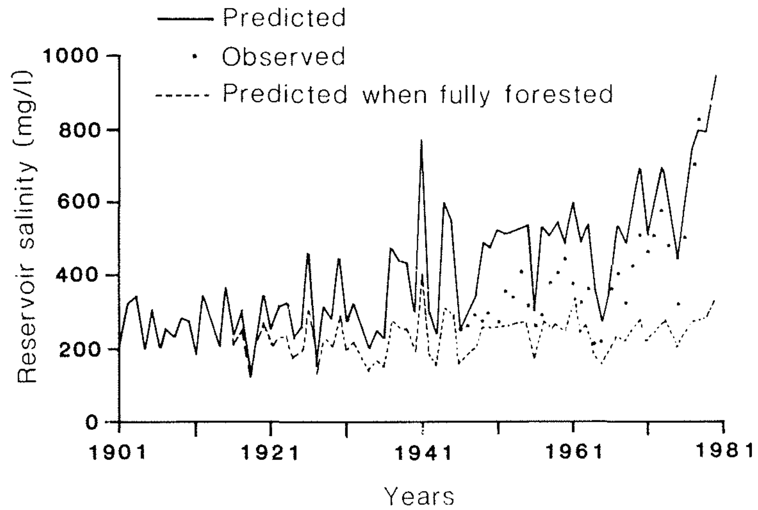
Application of the model to Wellington Dam involved dividing the catchment into nine zones based primarily on rainfall but with the Collie coal basin being treated as a separate zone. The annual flow and salt loads from each zone were summed to determine annual inflow volumes and salt loads to the Dam. For each zone the flow and salt load under forested conditions were augmented by the increase in flow and salt load from cleared areas. Under forested conditions flows were functionally related to rainfall, and salinities were generated from an equation describing the salinity-flow relationship. Salt load was simply the product of flow volume and salinity. Under cleared conditions, increased flows in each zone were calculated from another function of rainfall. The additional salt load was computed from the sum of overland/shallow subsurface salt discharge and groundwater salt discharge.

Although the model is simple in concept, it does require a significant amount of information for each zone. This includes: annual rainfall and annual cleared area; rainfall-runoff and salinity-flow relationships under forested conditions; rainfall-increased runoff relationship under cleared conditions; average overland/shallow subsurface salinity and average groundwater salinity; and groundwater discharge-recharge relationships as a function of time since clearing. In most cases generalised relationships were developed from data measured both within the catchment and from surrounding areas.

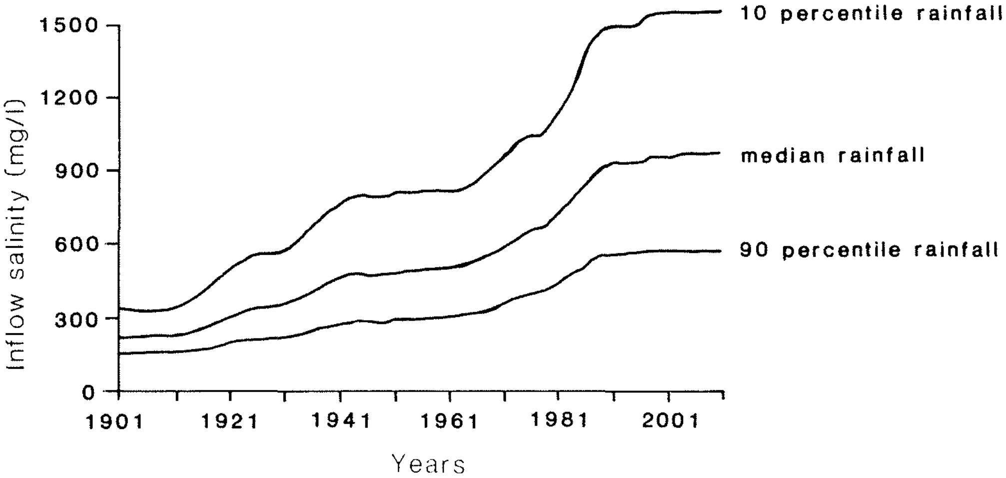
Clearing history and observed and predicted salinities for Wellington Dam are shown in Figure



**(a) Clearing history of Wellington Catchment**



**(b) Predicted and observed inflow salinities to Wellington Dam**



**(c) Predicted inflow salinities for extreme and average rainfall conditions**

**Figure 21: Prediction of Wellington Dam salinities** (after Loh and Stokes, 1980)

21a and b. The model gave good predictions after the mid-1960s but significant over-predicton prior to this time. A probable explanation of this over-prediction is the small groundwater discharge per unit area cleared resulting from the pre-1950 valley clearing compared to the relatively large groundwater discharge per unit area cleared resulting from the post-1950 upper slope clearing (see section 5.1.4).

The model was also used to predict future salinities assuming no further clearing took place, for high, median and low rainfall years (Figure 21c). The results highlight the large rainfall-salinity variability which occurs in agricultural catchments.

## 8.3 Schofield-Peck Model

Schofield (1988) presented a catchment mass-balance solute model for predicting stream salinity increases following agricultural clearing. An earlier version of the model was described by Peck (1976). The model was validated on Wights catchment (see Figure 8) and applied regionally to the high, intermediate and low rainfall zones of the south-west region. The predicted and 'observed' stream salinity increases are shown in Table 12. The 'observed' stream salinity increases were obtained by subtracting the mean salinity of catchments with agricultural clearing from the mean salinity of fully forested catchments within a particular rainfall zone.

**Table 12: Predicted and observed average stream salinity increases for different rainfall zones** (from Schofield, 1988)

| | **Stream salinity (TSS) increases** | |
|---|---|---|
| | Predicted (mg/L) | Observed (mg/L) |
| High rainfall zone (>1100 mm/yr) | 68 | 113 |
| Intermediate rainfall zone (900–1100 mm/yr) | 272 | 429 |
| Low rainfall zone (<900 mm/yr) | 3416 | 2387 |

The model under-predicted for the high and intermediate rainfall zones but over-predicted for the low rainfall zone. The over-prediction may be because the full effects of agricultural clearing on stream salinity are not yet manifest. However the 'observed' salinity increase in this rainfall zone is very sensitive to the catchments selected (see Table 8).

# 9. *Salinity Management of Surface Water Catchments*

## 9.1 Classification of Catchments by Salinity Hazard

A scheme of classifying catchments of south-west Western Australia with respect to stream salinity was proposed by Sadler and Williams (1981). They used the concept of 'salt hazard' which is taken to mean the potential of changing an area currently yielding potable water to one yielding unpotable water. The classification of Sadler and Williams (1981) has been modified and updated to provide more comprehensible and consistent groupings. The group names and criteria are given below. The catchments of each group are listed in Table 13.

GROUP 1
*Low Salt Hazard Catchments*

These catchments have low salt storage and their stream salinities remain fresh irrespective of loss of forest cover. Included are all catchments lying wholly in high rainfall areas (above 1100 mm/yr) and catchments on the coastal plain. The catchments are generally small but their streams are often high yielding.

GROUP 2
*Forested Catchments with Significant Salt Hazard*

These catchments extend inland of the 1100 mm isohyet to encompass areas where land use changes could cause significant stream salinity increase, but where most or all of the sensitive land at present is protected by State Forest. The rivers of Group 2 are fresh and will remain so as long as the State Forest is adequately protected. The group includes most of the important rivers already developed for water supply or irrigation.

GROUP 3
*Marginal Catchments*

Catchments which have moderate to high salt hazard and have been partially cleared for agriculture inland of the 1100 mm isohyet. The stream salinities are generally within or close to the marginal category (500–1000 mg/L TSS) and most have an increasing trend. The streams with increasing salinities could be maintained at, or restored to fresh or marginal levels with prompt and adequate rehabilitation measures.

GROUP 4
*Extensively Cleared Catchments*

Catchments which are predominantly freehold land where agriculture is the most extensive land use and has caused the main river to become brackish or saline. These catchments, though salt affected, still retain some forest and consequently have some potential for future water supply.

GROUP 5
*Almost Totally Cleared Catchments*

In these catchments agricultural land use is completely dominant with very little forest or other areas yielding potable water. The streams are brackish or saline.

The above classification of catchments is the basis of salinity management strategies. Most attention to date has been focused on groups 1 to 3. Some catchments have been subjected to legislative controls on land alienation (release for agriculture) and clearing while others are managed with a policy of high protection.

Tsykin E. N. (personal communication, 1988) has argued that salinity management based on regional salt storage ignores the considerable variations in local salt storage which could possibly allow the safe development of agriculture in some lower rainfall areas. While this could be the case, management to date has taken the simpler regional legislative approach, recognising the difficulties in determining local low salt hazard areas and the confusion that could arise from a detailed farm by farm decision process.

## 9.2 Land Alienation and Clearing Control Legislation

The need to control both clearing and release of Crown land on water supply catchments was recognised in the early part of the century on Mundaring catchment. During the 1950s the need to control further alienation of Crown land on Wellington catchment was recognised when the dam was being raised to meet additional irrigation water demand and to provide the source for the Great Southern Towns Water Supply Scheme. Administrative action to control the release of Crown land on Wellington Dam catchment and

**Table 13:**
**Catchment grouping by salinity hazard** (Details of the gauged catchments are given in Appendix A.)

**GROUP 1**
- Abba R.
- Angove Ck.
- Bancell Bk.
- Barlee Bk.
- Bickley Bk.
- Bow R.
- Brunswick R.
- Buayanyup R.
- Carey Bk.
- Chapman R.
- Churchman Bk.
- Clarke Bk.
- Collier R.
- Crooked Bk.
- Dirk Bk.
- Dombakup Bk.
- Drakes Bk.
- E. Kordabup Ck.
- Ellen Bk. (610)
- Fly Bk.
- Gardner R.
- Gooralong Bk.
- Harvey R.
- Henty Bk.
- Joshua Ck.
- King Ck.
- Lefroy Bk.
- Little Dandalup R.
- Logue Bk. (613)
- Ludlow R.
- Marrinup Bk.
- Meerup Bk.
- Munday Bk.
- N Dandalup R.
- Sabina R.
- Samson Bk.
- Scotsdale Bk.
- Scott R.
- Sleeman R.
- Stinton's Bk.
- Vasse R.
- Walpole R.
- Weld R.
- Wellesley Ck.
- W. Kordabup Ck.
- Wungong Bk.

**GROUP 2**
- Bolganup Ck.
- Canning R.
- Deep R.
- Donnelly R.
- Lyall Mill Str.
- Margaret R.
- Mitchell R.
- Serpentine R.
- Shannon R.
- S Dandalup R.

**Blackwood Tribs.**
- Balingup Bk.
- Dalgarup Bk.
- Gregory Bk.
- Rosa Bk.
- St John Bk.

**Collie Tribs.**
- Bingham R.
- Harris R.

**Murray Tribs.**
- Bell Bk.
- Big Bk.
- Chalk Bk.
- Davis Bk.
- Howse Bk.
- Logue Bk. (614)
- Long Gully
- Nanga Bk.
- Swamp Oak Bk.
- Yarragil Bk.
- 34 Mile Bk.

**GROUP 3**
- Capel R.
- Collie R.
- Denmark R.
- Ferguson R.
- Helena R.
- Kent R.
- Marbellup Bk.
- Preston R.
- Quickup R.
- Warren R.
- Waychinnicup Ck.

**Avon Tribs.**
- Ellen Bk. (616)
- Jane Bk.
- Julimar Bk.
- Lennards Bk.
- Susannah Bk.

**GROUP 4**
- Blackwood R.
- Frankland R.
- Hay R.
- Murray R.

**Avon Tribs.**
- Brockman R.
- Jimperding Bk.
- Red Swamp Bk.
- Wooroloo Bk.

**GROUP 5**
- Avon R.
- Kalgan R.
- King R.
- Lort R.
- Pallingup R.
- Young R.

Note: Tributaries with the same salinity hazard as its main river have been omitted.

the Kent and Denmark River catchments proceeded in 1961. In 1978 a State Cabinet decision was made to halt all alienation of Crown land between the Collie River and the Kent Rivers (Figure 22) to protect other potential water reserves in the lower south-west.

Through the 1960s there was a growing awareness that control of alienation of Crown land would not be sufficient to maintain satisfactory salinity levels in a number of major water resources. Action would be required to halt clearing on land already alienated. In 1976 amendments to the Country Areas Water Supply Act (1947) were passed by both Houses of Parliament. The legislation made it an offence to clear or destroy native vegetation without a licence. The legislation was applied initially to the catchment of Wellington Dam. In 1978 the legislation was extended to four other critically important water resource catchments. These were Mundaring reservoir catchment and the Denmark, Warren and Kent River catchments (Figure 22). The catchments were carefully selected to represent those most sensitive to further agricultural expansion.

Catchments which had brackish or saline streams which could not be easily returned to potable levels (Groups 4 and 5) were not included under the legislation. Also not included were catchments that drained predominantly State Forest and were fresh and unlikely to become saline if the small amounts of private land in their catchments were cleared (Groups 1 and 2).

Under the clearing control legislation small scale essential clearing is licenced but large-scale agricultural development is not permitted. Affected farmers can claim compensation for their inability to further develop their farm enterprise.

The clearing controls have restricted agricultural development from approximately 1200 square kilometres in the more reliable rainfall areas of the south-west. Nevertheless this represents only 0.7% of the 180 000 square kilometres of farmland within private holdings in the agricultural areas of south Western Australia. Loss of this agricultural production potential has been accepted as a necessary consequence of protecting the five most important marginal water resources. The total expenditure on compensation associated with clearing controls has been about $35 million over the last 11 years (Water Authority of Western Australia, 1988).

Administration of the clearing control legislation has not been without its difficulties. Initial problems in the definition of clearing arose where regrowth had occurred following earlier clearing. Also some areas of forest, usually the smaller clumps of trees in grazing areas, for which compensation has been paid, have not been fenced to exclude stock. The long term protection and regeneration of these areas is of serious concern. Although it is the responsibility of the landowner to ensure the maintenance of the indigenous bush, identifying any gradual decline in forest cover will be difficult and implementing remedial action will be a major limitation to protection of remaining bush in farmland with the high cost of fencing.

## 9.3 Protection of Forested Catchments

A cornerstone of the regional strategy of salinity management has been the need to protect the existing forest cover on public land. Where there has been any concern that forest or mining operations in State Forest may lead to salinity problems, extensive research programmes have been undertaken. Results from these programmes have greatly improved our knowledge of the stream salinity problem.

In the case of intensive logging and clearfelling and regeneration of southern forests, research indicates that through appropriate management there will be no significant threat to the water quality of regional water resources (Steering Committee for Research on Land Use and Water Supply, 1987a).

To date Alcoa's bauxite mining operations in the northern Jarrah Forest have been constrained to the western high rainfall zone of the Darling Range where the salinity risks are low. No increases in stream salinities have been recorded from their current mining and rehabilitation practices (Steering Committee for Research on Land Use and Water Supply, 1984). Future bauxite mining in the intermediate rainfall zone has been restricted until research shows that such operations can take place without adversely affecting stream salinity. Experience to date would suggest the risks of salinity increase are relatively low. However, the long term control of the spread of dieback disease (*Phytophthora cinnamomi*) and the development of appropriate intermediate rainfall zone rehabilitation strategies require research and evaluation. There is sufficient time to develop these control methods before Alcoa will wish to mine in this zone.

The protection of State Forest has been threatened in recent times by spread and intensification of the

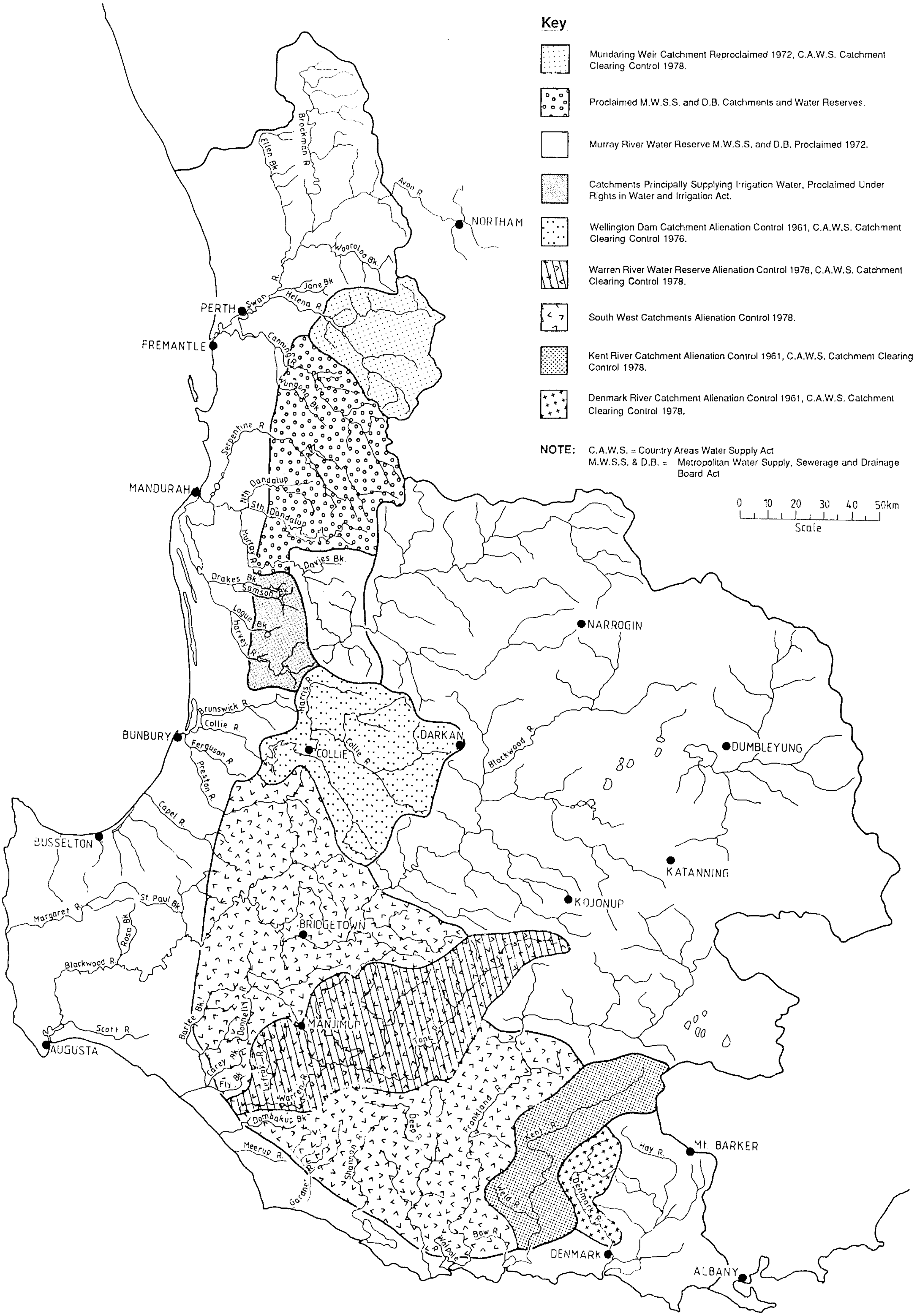


Figure 22: Land alienation and clearing control legislation boundaries

root rot fungus *Phytophthora cinnamomi* which causes the condition known as jarrah dieback. This disease has been observed for several decades but its spread has escalated dramatically over the last two decades to cover some 14% of the jarrah forest, mostly affecting high rainfall areas (Forests Department W.A., 1982). On susceptible sites the disease results in complete mortality of the overstorey and dramatic decline in the diversity and vigour of the understorey (Podger, 1972). The substantial diminution in crown cover has resulted in increased water and salt export from affected catchments (Schofield *et al.*, in press). It is essential that the development of forest management practices to control the spread and intensification of dieback disease in the jarrah forest is continued.

A more recent concern for the protection of State Forest is attack from insect epidemics. Two insect pests, leaf miner (*Perthida glyphopa*) and gumleaf skeletonizer (*Uraba lugens*) currently infest 53% of the jarrah forest, predominantly in the southern forests. Jarrah leaf miner, however, is spreading northwards rapidly and is projected to reach Dwellingup by 2010 and Mundaring by 2040. The leaf miner caterpillars defoliate jarrah between June and October-November each year but new spring growth re-establishes a crown within months. To date crown damage by insects has not led to mortalities although substantial crown deterioration has occurred and there is the potential for mass collapse. The impact of crown damage on transpiration is unknown. The consequence for water resources could be significant if the current broad area of infestation became chronic and caused a permanent reduction in annual tree transpiration. Increased efforts in the study of insect problems in the jarrah forest are therefore justified.

## 9.4 Salinity Status of the Marginal (Group 3) Catchments

The Marginal salinity hazard catchments (Group 3, Table 13) comprise 31% of the potable water resources of the south-west region, but 77% of this resource is in the marginal salinity category and deteriorating. The status of nine of these catchments is given in Table 14. The 5 year moving average salinity trends for some of these catchments are shown in Figure 23.

The prediction of future maximum stream salinities resulting from past agricultural clearing have been computed for some Group 3 catchments (Table 14) using the Loh and Stokes (1981) model described in Section 8.

### *(i) Collie River (Wellington Dam)*

The predictions for the Collie River were based on data from Mungalup Tower gauging station (612002) which is the first station upstream of Wellington Dam, representing 90% of the Wellington Dam catchment area. The current median stream salinity is some 300 mg/L TSS below the predicted maximum median salinity, indicating a significant potential for further salinity increases in the absence of reforestation. The Wellington Dam itself is subject to a potential increase from a median salinity of about 850 mg/L TSS (in 1984) to a maximum of 1150 mg/L TSS (Water Authority of Western Australia, 1985). The estimated rate of salinity increase for the Collie River at Mungalup tower is very high (42 mg/L/yr) and is statistically significant at the 4% level (Table 14).

### *(ii) Helena River (Mundaring Reservoir)*

Predictions for the Helena catchment are based on five tributaries upslope of Mundaring reservoir which represent 92% of the Helena catchment area determined at the location of the lower Helena pipehead dam. For the five tributaries it appears that the median salinity has already attained the predicted maximum salinity. The regression on annual salinities shows a very slight increase but this should be regarded as 'near zero change'. The salinity of Mundaring reservoir itself is considerably lower than the above mentioned tributaries, ranging from 400 to 600 mg/L TSS in recent years. This is because the 8% of the catchment adjacent to the reservoir and between the reservoir and the downstream pipehead dam are not included in the above tributaries. This area produces 25–60% of the inflow volume, depending on annual rainfall, at low salinity.

### *(iii) Denmark River*

Salinity predictions for the Denmark catchment were updated by Ruprecht *et al.* (1985). Three catchment zones were used, based on existing gauging stations. The predicted future maximum median salinity was 730 mg/L TSS which is only 100 mg/L TSS greater than the current median salinity, and somewhat less than the 1981–86 average. The current high rate of salinity increase of 26 mg/L/yr has a high statistical significance and suggests that the predicted maximum of 730 mg/L is probably low.

As a result of the deteriorating salinity levels in the Denmark River and town water supply, the Water Authority commenced construction of a new storage on the Quickup River in 1988. The Quickup River enters the lower reaches of the

## Table 14: Characteristics and salinity predictions for some marginal catchments (Group 3 salinity hazard)

| River | NGSN | Period of record | Catchment area | State Forest & Reserves | Private land |  | Average annual salinity (1981–86) | Median(3) flow salinity | Rate of salinity increase since 1965 | Stat. signif. | Predicted(4) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Uncleared | Cleared |  |  |  |  | Maximum salinity from clearing to date | Date at which maximum salinity reached |
|  |  |  | (km²) | (%) | (%) | (%) | (mg/L) | (mg/L) |  |  | (mg/L/yr) | (mg/L) |
| Collie | 612002 | 1969-86 | 2550 | 65(6) | 12(6) | 23(6) | 1069 | 1030 | 42 | 0.039 | 1350 | 2040 |
| Helena | multiple(1) | variable | 1358 | 95(7) | 2.5(7) | 2.5(7) | 688(2) | 780 | 1(5) | 0.04 | 900 | - |
| Denmark | 603136 | 1960-86 | 567 | 79 | 5 | 16 | 910 | 630 | 26 | 0.0001 | 730 | 2005 |
| Warren | 607220 | 1940-86 | 4040 | 54 | 14 | 32 | 854 | 770 | 15 | 0.0056 | 1270 | - |
| Kent | 604053 | 1956-86 | 1850 | 45 | 15 | 40 | 1750 | 1190 | 58 | 0.0002 | 1500 | - |
| Susannah | 616040 | 1981-86 | 25 | - | 60 | - | 360 | 360 | 7 | 0.28 | - | - |
| Ellen | 616189 | 1965-86 | 590 | - | 65 | - | 530 | 560 | 1 | 0.77 | - | - |
| Preston | 611049 | 1955-75 | 603 | - | 50 | - | 354(5) | 380 | 8 | 0.037 | - | - |
| Capel | 610129/ 219 | 1959-76 | 332 | - | 50 | - | 423(5) | 560 | 15 | 0.018 | - | - |

(1) 616010, 616002, 616216, 616007, 616009

(2) based on salinity-flow relationship for 1975–86

(3) based on 1974-86

(4) maximum values attained, allowing for time lags

(5) based on last 5 years of record

(6) based on catchment area defined by gauging station 612033

(7) based on catchment area defined by gauging station 616003

Denmark River and is 10–15% cleared. Two years of record (1985–86) from a gauging station downstream of the dam site showed an average stream salinity of 585 mg/L TSS, which is in the marginal category. As a result of this relatively high salinity and other dam design considerations, the final dam site was located upstream where the proportion of clearing in the catchment is less than 3%. This cleared area is being partially reforested in conjunction with the reservoir development.

### *(iv) Warren River*

The maximum stream salinity prediction for the Warren catchment was updated by Bell *et al.* (1987) to 1270 mg/L TSS. Current median and average annual salinities are well below this value (Table 14) suggesting that there remains a considerable potential for further salinity increases.

### *(v) Kent River*

The Kent River salinity predictions have not been updated since 1981. The current median salinity is some 300 mg/l TSS below the predicted maximum but the rate of increase is currently very high (58 mg/L/yr). The 1982–86 average annual stream salinity has been well above the predicted maximum median salinity (Table 14).

### *(vi) Preston River*

The Preston River gauging station 611049 was closed in 1975. A new gauging station (611004) was constructed in 1981 about 20 km downstream. Over the period 1981–86 the average stream salinity was 390 mg/L TSS and statistical analysis showed an increasing trend of 20 mg/L/yr, although this was of low statistical significance.

### *(vii) Thomson River*

The average salinity of Thomson River (611111), an upstream tributary of the Preston River, over the period 1957–85, was 534 mg/L TSS. The rate of salinity increase over this period was 18 mg/L/yr which was highly significant ($p<0.001$). The trend is shown in Figure 23. These results indicate that significant parts of the Preston River are of marginal salinity and the resource as a whole is deteriorating.

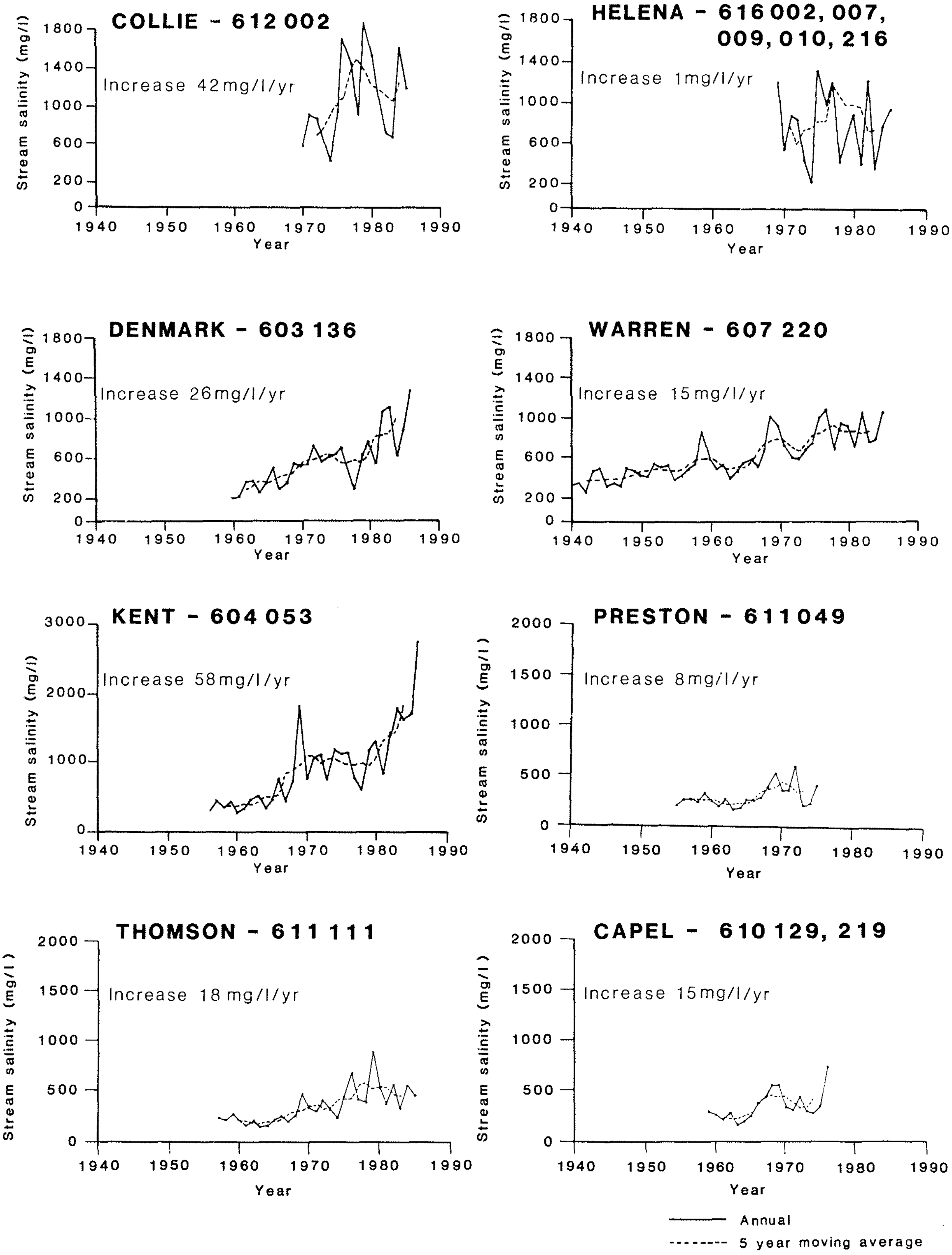


Figure 23: Stream salinity trends of some marginal catchments (Group 3 salinity hazard)

*(viii) Capel River*

The Capel River is within the Busselton Coast region and is currently not considered a divertible water resource. Gauging stations 610129/219, which operated over the period 1959–76, recorded a rate of salinity increase of 15 mg/L/yr ($p<0.02$). The average stream salinity from 1972–76 was 423 mg/L TSS (fresh) but now could be well in the marginal category.

*(ix) Avon tributaries (Ellen, Jane and Susannah Brooks)*

Jane Brook and Susannah Brook are fresh tributaries of the Avon River and have been included in Group 3 because both catchments have significant proportions of their catchments alienated but not cleared. Since there are no clearing controls in these catchments there is potential for further salinity deterioration. Ellen Brook, another Avon tributary, has a current average stream salinity in the marginal category. Model simulations for Jane, Susannah and Ellen Brooks (see Section 8.1) indicate that current salinities will rise to 449, 401 and 630 mg/L TSS repectively with no further clearing (Table 11). In the case of full clearing the investigation suggests that the average salinity of Ellen Brook could drop markedly to 380 mg/L TSS.

## 9.5 Potential Surface Water Supplies in the South-West

As south-west Western Australia continues to develop over the next 50 years, the demand and competition for water and land resources will intensify. Identification of important regional water supply sources and the development of catchment plans to protect and improve their water quality is, therefore, of high priority. Table 15 highlights the major resources of importance to the Perth–Bunbury region. Current salinities and statistically significant ($p<0.05$) trends in salinity are included.

The total potentially divertible water resource is 730 million cubic metres per annum but slightly over half of this amount is in catchments which have significantly increasing salinities. The main catchments of concern are the Warren, Preston and Collie Rivers. The salinity management of these catchments will need high priority if their full water resources potential is to be realised.

**Table 15: Potential surface water supplies and their salinity characteristics**

| | Dam(1) site | Mean annual flow | Divertible resources | Mean annual salinity | Salinity(2) trend |
|---|---|---|---|---|---|
| | | ($10^6m^3$) | ($10^6m^3$) | (mg/L) | (mg/L/yr) |
| WARREN BASIN (607) | | | | | |
| Warren R. | DS27 | 350 | 245(3) | 870 | +15 |
| Dombakup Bk. | DS1.6 | 44 | 31 | 150 | - |
| Big Bk. | DS1 | 18 | 14 | | |
| Lefroy Bk. | DS24 | 16 | 13 | 190 | - |
| DONNELLY BASIN (608) | | | | | |
| Fly Bk. | DS3 | 22 | 16 | 140 | - |
| Carey Bk. | DS1 | 39 | 27 | 120 | - |
| Donnelly R. | DS26 | 144 | 100(3) | 220 | - |
| Barlee Bk. | DS21 | 29 | 20 | 160 | - |
| BLACKWOOD BASIN (609) | | | | | |
| St John Bk. | DS10 | 75 | 51(3) | | - |
| BUSSELTON COAST BASIN (610) | | | | | |
| Margaret R. | D17 | 102 | 51 | 200 | - |
| PRESTON BASIN (611) | | | | | |
| Preston R. | DS51 | 79 | 27 | 3504 | +8(4) |
| Joshua Ck. | DS3 | 9 | 3 | | |
| Ferguson R. | DS20 | 19 | 163 | 2305 | +1(5) |
| COLLIE BASIN (612) | | | | | |
| Brunswick R. | DS26 | 78 | 53 | 230 | - |
| Collie R. | D37 | 220 | 43(6) | 1070 | +35(7) |
| Collie R. | DS24 | 88 | 20 | 720 | ? |
| | | TOTAL | 730 | | |

(1) Dam sites are listed in Western Australia Water Resources Council (1987b)

(2) only shown where significant at $p<0.05$

(3) unlikely to be fully developed for water supply

(4) for period 1955–75 only

(5) for period 1960–73 only

(6) the divertible resources for the Collie R. are those above current utilisation

(7) based on Wellington Reservoir salinity rather than Mungalup Tower gauging station

## 9.6 Further Salinity Management Requirements

Although often implemented later than desirable, the controls on alienation of Crown land and on clearing in critical water resource catchments have been partially successful in limiting further large-scale salinity deterioration. The total expenditure on compensation associated with clearing controls of about $35 million over the last 11 years remains the least costly measure available for controlling stream salinity. Nevertheless stream salinities of the Collie, Denmark, Warren, Kent and Preston Rivers are still increasing rapidly as a result of past agricultural clearing. If these catchments are to remain as viable water resources for future Perth and local water supplies then supplementary action is required to halt stream salinity increases. A range of possible options was considered in the late 1970s (Public Works Department, 1978) and it was concluded that partial catchment reforestation was the most promising approach in most cases. As a result partial reforestation of the Collie catchment was commenced in 1979/80. In some cases, such as the Kent River, a combination of engineering and catchment management measures may be appropriate in the future. More recently an integrated catchment management approach involving both forestry and agricultural strategies has been adopted for the Denmark catchment. These and other revegetation strategies are described at length in a companion report (Steering Committee for Research on Land Use and Water Supply, 1989).

# *10. Future Requirements for Salinity Management*

## 10.1 Catchments Requiring Further Salinity Management

One objective of this report is to determine the management priorities of catchments needing further salinity management. The priorities for rehabilitation will depend on the magnitude of the resource, the planned timing of its development, the cost-efficiency of its development, its conservation and recreation values and its salinity status.

The Wellington Dam (Collie R.) and the Denmark River have already been identified as priority management catchments. Active management of these catchments is already taking place. The other potential water supply catchments needing further salinity management are the Warren, Kent and Preston.

The Wellington Dam catchment is a good example of the importance of planning rehabilitation well in advance of the utilisation need. In this case the need for water supply overtook the rehabilitation programme. This has led to considerable capital expenditure for the construction of a second dam on a fresh tributary to provide water to the Great Southern Towns Water Supply Scheme.

There are no plans to attempt to totally rehabilitate brackish and saline river catchments (salinity hazard Groups 4 and 5—Table 13) for water supply purposes. Many of these catchments currently have rapidly increasing stream salinity (see Table 10 and Appendix B). The most significant water resources in this category are the Murray River, Blackwood River and Avon River. The water supply development strategy adopted for these rivers is to utilise fresh water tributaries in the forested areas of their catchments. Some of the potential water supply of the Murray River has been allocated to environmental uses with the declaration of the Lane Pool Reserve. Other environmentally important areas of brackish and saline catchments may require protection or rehabilitation (see Section 10.3).

## 10.2 Small Town Water Supplies

Small town water supplies are particularly sensitive to annual or seasonal stream salinity variation because the supply storages are small and there is little 'damping' of the salinity variation. As flow-weighted mean stream salinities increase, the salinity maxima increase at a faster rate. The well-below-average rainfall of the last decade has led to some particularly high stream salinities and emphasised the severity of the problem. Two small town water supplies (Balingup and Denmark) were so adversely affected that expensive alternative sources had to be constructed. Other small water resources which have the potential to develop similar salinity problems should be identified and appropriate management strategies developed.

## 10.3 Salinity as a Conservation Issue

Salinity is most frequently considered in terms of its damage to the productive capacity of land and the loss of water supply value of water. It has received much less attention in terms of its impact on the conservation of lake and riverine ecosystems. These effects have been dramatic and widespread.

Within State Forest the major effects from salinity are a change in mean (about five fold) and peak (about ten fold) salinities of the intermediate and long rivers which have some proportion of low rainfall zone farmland on their catchment.

The biological significance of these changes has not been studied in any detail. However, it is likely that salinity changes of this order will have eliminated some species of aquatic invertebrates which have very specific water quality requirements.

The small and transient impacts on salinity in forest streams after intensive forest operations (Steering Committee for Research on Land Use and Water Supply, 1987a) have also not been scrutinized in any detail for biological impact. However such effects would appear to present little risk.

Throughout the inland agricultural areas the salinity status of lakes and rivers has been dramatically altered. The expression of salt mobilisation occurs in low lying areas including swamps and stream courses, resulting in almost complete loss of plant communities characteristic of these areas. Thus, swamp vegetation dominated by *Casuarina obesa* (swamp sheoak), *Melaleuca* species (paperbarks) and various species of sedges, which used to be abundant throughout much of the

Wheatbelt, has now been eliminated from most areas of the low rainfall zone.

Lake Toolibin, almost the last of these sheoak/paperbark wetlands, and itself threatened with increasing salinity, has been found to support more breeding species of waterbirds than any other wetland in south-west Western Australia (Northern Arthur River Wetlands Committee, 1987). The loss of similar timbered wetlands, which has already occurred throughout most of the low rainfall zone, would be expected to have reduced substantially the breeding success of many species of waterbirds, including *Stictonetta naevosa* (Freckled Duck), a gazetted rare and endangered species. Currently Lake Toolibin is the most important wetland in the south-west for the Freckled Duck.

Other important wetlands throughout the low rainfall zone are currently undergoing gradual increases in salinity. This is likely to result in the eventual death of fringing paperbarks and dense swamp vegetation in most small wetland nature reserves throughout the wetter parts of the low rainfall zone. For instance, many of the freshwater swamps and lagoons in the Lake Muir Nature Reserve have at least part of their catchments in cleared farmland. These wetlands have acted as freshwater refuges throughout the Pleistocene, and support species of invertebrates which are very selective of low salinity waters and which have been found nowhere else. These species may be lost altogether if the increasing trend in salinity continues.

In summary, freshwater wetlands, taller trees and denser vegetation associated with better watered low lying areas are becoming rare throughout the low rainfall zone as a result of increasing salinity. The implications of this for the conservation of the vegetation itself, aquatic invertebrates, waterbirds and other fauna concentrated around these areas are extremely grave.

## 10.4 Integrated Catchment Management Planning

Water resources planning in Western Australia is at a stage where future potential sources can be identified and possible development schedules specified. Although source selection is still at the planning stage, the likelihood of the need to harness sources in the lower south-west in the next 60 years to meet the demands of the Perth region is increasing. Along with this long term planning there is a need to specify in more detail the status and management needs of specific sources.

The logical approach is to develop catchment plans, particularly where some advanced management activity is required. Since such catchment planning encompasses various land uses, including forestry, agriculture, urban, conservation, recreation etc., there is a clear need to integrate the catchment planning process. Such an integrated approach is actively being pursued by the State Government with the formation of the Integrated Catchment Management Policy Group.

# *11. Future Research Requirements*

The major research effort in the 1970s and 1980s has greatly clarified our understanding of the mechanisms and processes involved in stream salinisation following agricultural development. Such a detailed understanding of the problem has been necessary for appropriate management solutions to be found. Future research can now be targeted to meet current and emerging management problems. The following areas related to the impact of agricultural clearing on stream salinity still require attention:

- Further studies of the water and salt flows from catchments following clearing are required to determine the behaviour of stream salinity over time. In particular knowledge is required of the likely duration of the phases of increasing salinity and decreasing salinity (to a new equilibrium) for a range of conditions. For this purpose a number of the existing experimental catchments should continue to be monitored for a number of years.
- The ability to predict future stream salinities of large water resource catchments should be upgraded. This involves continuing high quality streamflow and salinity monitoring and the development of improved models. Application of improved models will enable a better assessment of management options and priorities.
- Research should be carried out into the potential impact of the Greenhouse Effect on agriculturally-induced stream salinity. Prevailing opinion at the present time is that average rainfall in the south-west region could decrease by as much as 20% and streamflow by 40% by 2040. This would cause a very significant increase in stream salinities similar to that experienced in low rainfall years.
- To date little attention has been given to the impact of salinity on conservation of lake and riverine ecosystems. Studies should be initiated to examine the impact of land disturbances in forested catchments which are likely to affect water quality. Most effort, however, should be directed at identifying, assessing and developing management strategies for the remaining freshwater wetlands in the agricultural areas. The conservation values of these sites are very high but are under serious threat from salinity.

Most future research should be devoted to rehabilitation of salt-affected catchments and protection of fully forested catchments subject to non-agricultural land disturbances. The research requirements of rehabilitation are described fully in the companion report (Steering Committee for Research on Land Use and Water Supply, 1988).

# 12. Conclusions

- The development of Western Australia has relied heavily on introduced annual crops and pastures which led to vast tracts of land being cleared of its native vegetation in the south-west of the State.
- It was clearly established by the 1920s that clearing of native vegetation would lead to significantly increased stream salinity in all except the high rainfall areas of the Darling Range. However no legislative action to control land alienation or clearing in water resource catchments was taken until the mid-1970s.
- Today, stream salinisation has increased to the extent that only 48% of the divertible surface water resources of the south-west remain fresh (less than 500 mg/L TSS). A further 16% is marginal, while 36% is no longer potable.
- While the stream salinities of fully forested catchments have generally decreased over the last decade, rapid increases in stream salinity are occurring in catchments which extend inland to below the 1100 mm/yr rainfall isohyet and which are partially developed for agriculture.
- Whether or not agricultural development will cause substantial increases in stream salinity depends primarily on the quantity of salt stored in the catchment. Salt storage in turn is closely correlated with annual rainfall. In areas with rainfall greater than 1100 mm/yr, agricultural clearing is unlikely to increase stream salinity beyond the fresh limit (500 mg/L TSS). However below 1100 mm/yr rainfall, stream salinities are likely to become marginal, brackish or saline. The prognosis is worse the lower the rainfall.
- The magnitude of the stream salinity response is also affected by the proportion and location of agricultural clearing. There is a clear trend for stream salinity to increase with area cleared, and for the rate of salinity increase with area to be greater the lower the average rainfall. Large stream salinity increases may occur in response to a small percentage (<30%) of clearing in low rainfall areas. Historically clearing took place initially on the valley floors and led to some increase in stream salinity in salt prone areas. Further clearing upslope of the valley floor rapidly augmented stream salinity increases.
- Streamflow has increased by as much as four times following agricultural clearing. However, in nearly all cases, the dilution effect of increased streamflow has not been sufficient to offset the increased salt discharge (primarily from groundwater), and so stream salinity has increased.
- Legislative controls on land alienation and clearing, although applied later than desirable, were a major first step in reducing further stream salinity increases on some important marginal catchments. Further active catchment management is required to halt or reverse the continuing salinity deterioration on these catchments. To this end partial reforestation of the Wellington Dam catchment has been underway since 1980.
- Groundwater recharge appears to be dominated by areas of local preferred flow. Most of the recharge bypasses the salt stored in the soil profile. This implies that agricultural clearing would have little impact on the vertical leaching of salts. The rapid rate of downward water movement in these preferred recharge areas further implies that shallow-rooted agricultural plants would not be appropriate for reducing such recharge.
- Six major water resources catchments have been highlighted as requiring the initiation or continuation of salinity management. These are the Collie, Helena, Denmark, Warren, Kent and Preston River catchments. A number of smaller water resources also have the potential to develop salinity problems and should be kept under review.
- Massive biological change has taken place in wetlands and streams of low rainfall areas due to increasing salinity. This has been poorly documented. Work is required to identify, assess and manage sites of high conservation value which are under threat of salinity.
- Considerable progress has been made since the early 1970s in understanding the salinity problem. Future research should focus on protection of forested catchments subject to non-agricultural disturbances and amelioration of the marginally salt-affected catchments. Better assessment of the management options will result when further research allows more accurate predictions of the time courses of future stream salinities. The implications of the Greenhouse Effect-driven climatic change for streamflow and stream salinity are particularly important in this regard.

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# *Appendix A: Characteristics of South-West Catchments (Groups I–IV)*

## Key to tables

**Date of major clearing**

N/a = Not available

**Land use**

a = Agriculture (pasture, cereals, beef, sheep)
b = Mining (usually Bauxite mining)
f = Forest
m = Mixed farming (agriculture plus orchards, intensive crops etc.)
n = Native vegetation other than forest
p = Softwood plantation
Note: when more than one land use, order represents predominance

**Natural vegetation**

h = Heath
j = Jarrah-marri
jmw = Jarrah-marri-wandoo woodlands
jw = Jarrah-wandoo woodland
k = Karri
kj = Karri-jarrah
lw = Low woodland
m = Mallee
mjs = Mallee heath/jarrah-sheoak woodland
mw = Marri-wandoo woodland
sh = Scrub heath
t = Thickets
wm = Wandoo-mallee
wy = Wandoo-York gums
xw = Mixed woodland
ys = York-Salmon gums
yw = York-wandoo woodland

**Stream gauge status**

1 = Stream is gauged downstream at one location
2 = Stream is gauged downstream at two locations
3 = Stream is gauged downstream at three locations

## **Group I: Major rivers** (Excludes catchments where gauging commenced after 1980)

| Gauging station number | Stream name | Location name | Area (km$^2$) | Period of record | Long term mean rainfall | Mean runoff (mm) | Mean salinity (mg/L) | Area cleared (%) | Date of major clearing | Land use | Natural vege-tation | Stream gauge status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 601001 | Young R | Neds Corner | 1601 | 1971–82 | 460 | <1 | 5907 | 75 | 1960 | n,a | m | |
| 603002 | Denmark R | Lindesay Gorge | 466 | 1973–82 | 920 | 47 | 761 | 16 | 1950 | f,a | j | 1 |
| 603003 | Denmark R | Kompup | 235 | 1974–82 | 950 | 49 | 1293 | 32 | 1950 | f,a | j | 2 |
| 603136 | Denmark R | Mount Lindesay | 525 | 1960–86 | 960 | 62 | 511 | 17 | N/a | f,a | j | |
| 603173 | Denmark R | Clear Hills | 225 | 1962–78 | 950 | 44 | 841 | 30 | 1950 | f,a | j | 3 |
| 604001 | Kent R | Rocky Glen | 1110 | 1979–82 | 655 | 19 | 3201 | 65 | 1950 | a,f | j | 1 |
| 607003 | Warren R | Wheatley Farm | 2910 | 1970–82 | 735 | 29 | 2159 | 40 | 1960 | a,f | j | 1 |
| 607220 | Warren R | Barker Rd Crossing | 4040 | 1966–86 | 865 | 74 | 550 | 36 | 1950 | f,m | j | |
| 609012 | Blackwood R | Winnajup | 17600 | 1980–82 | 485 | 17 | 4772 | 90 | 1950 | a,f | xw | 1 |
| 609025 | Blackwood R | Darradup | 20500 | 1956–86 | 550 | 32 | 1400 | 85 | 1950 | a,f | xw | |
| 611004 | Preston R | Preston Bridge | 830 | 1980–82 | 970 | 98 | 397 | 60 | 1950 | m,f | j | |
| 612002 | Collie R | Mungalup Tower | 2550 | 1969–86 | 780 | 43 | 980 | 24 | 1970 | f,m | j | |
| 612019 | Bussell Bk | Duces Farm | 38 | 1977–82 | 1080 | 74 | 302 | 10 | 1930 | f,p,m | j | |
| 612152 | Brunswick R | Olive Hill | 228 | 1961–83 | 1225 | 295 | 232 | 25 | 1960 | f,m | j | |
| 614006 | Murray R | Baden-Powell Water Spout | 6840 | 1939–82 | 655 | 48 | 1677 | 75 | 1950 | a,f | j | |
| 615014 | Avon R | Brouns Farm | 96400 | 1975–82 | 230 | <1 | 6353 | 60 | 1950 | a,f | xw | 3 |
| 615021 | Avon R | Dunbarton Bridge | 115000 | 1977–81 | 350 | 1 | 8012 | 65 | 1950 | a,f | ys | 2 |
| 616011 | Avon R | Walyunga | 119000 | 1970–82 | 400 | 3 | 4414 | 65 | 1950 | a,f | m | |
| 616024 | Canning R | Scenic Drive | 517 | 1977–82 | 880 | 13 | 252 | 0 | - | f | j | 1 |
| 616216 | Helena R | Poison Lease | 585 | 1966–85 | 680 | 13 | 1304 | 10 | N/a | f,a | mw | |
| 617003 | Gingin Bk | Bookine Bookine | 826 | 1972–82 | 720 | 41 | 961 | 65 | 1950 | a,f | lw | |

### **Group II: Tributaries & minor rivers** (Excludes catchments where gauging commenced after 1980)

| Gauging station number | Stream name | Location name | Area (km²) | Period of record | Long term mean rainfall | Mean runoff (mm) | Mean salinity (mg/L) | Area cleared (%) | Date of major clearing | Land use | Natural vege- tation | Stream gauge status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 601004 | Lort R | Fairfield | 2800 | 1973–82 | 450 | 1 | 16270 | 60 | 1950 | n,a | m | |
| 601005 | Young R | Cascades | 85 | 1974–82 | 450 | 1 | 11988 | 25 | N/a | n,a | m | |
| 601006 | Young R | Munglinup | 9.3 | 1974–82 | 450 | <1 | 393 | 10 | N/a | n,a | m | 1 |
| 601600 | Young R | Melaleuka | 1.3 | 1974–82 | 450 | <1 | 145 | 0 | - | n | m | 2 |
| 602001 | Pallinup R | Bull Crossing | 3600 | 1973–82 | 400 | 5 | 19478 | 90 | 1950 | a,n | m | |
| 602004 | Kalgan R | Stevens Farm | 2860 | 1976–82 | 620 | 16 | 3104 | 65 | 1950 | a,n | m | |
| 603172 | Amuri Ck | Amarillup Swamp | 19 | 1962–77 | 875 | 86 | 893 | 50 | 1950 | f,a | j | 1 |
| 603177 | Perillup Bk | | 66 | 1962–73 | 875 | 30 | 294 | 15 | 1950 | f,a | j | |
| 603190 | Yate Flat Ck | Woonanup | 57 | 1963–82 | 900 | 95 | 891 | 60 | N/a | f,a | j | |
| 604053 | Kent R | Styx Junction | 1850 | 1956–86 | 815 | 46 | 930 | 40 | 1950 | f,a | j | |
| 605012 | Frankland R | Mt Frankland | 5800 | 1940–86 | 615 | 31 | 1430 | 85 | 1930 | a,f | mw | |
| 606001 | Deep R | Teds Pool | 458 | 1975–82 | 990 | 83 | 176 | 0 | - | f | j | |
| 606185 | Shannon R | Dog Pool | 350 | 1964–86 | 1195 | 241 | 167 | 3 | 1920 | f | k | |
| 606195 | Weld R | Ordnance Rd Crossing | 240 | 1964–86 | 1250 | 237 | 163 | 0 | - | f | k | |
| 606218 | Gardner R | Baldonia Creek Confluence | 419 | 1966–82 | 1200 | 291 | 162 | 17 | 1925 | f,m | k | |
| 607002 | Lefroy Bk | Channybearup | 92 | 1970–82 | 1130 | 166 | 271 | 55 | 1925 | m,f | k | 2 |
| 607004 | Perup R | Quabicup Hill | 645 | 1974–86 | 765 | 21 | 2898 | 19 | 1930 | m,f | j | |
| 607007 | Tone R | Bullilup | 1040 | 1978–82 | 630 | 18 | 4602 | 70 | 1950 | a,f | j | |
| 607009 | Lefroy Bk | Pemberton Weir | 257 | 1943–86 | 1220 | 234 | 180 | 30 | 1925 | f,m | k | |
| 607013 | Lefroy Bk | Rainbow Trail | 254 | 1979–82 | 1220 | 160 | 189 | 30 | 1925 | f,m | k | 1 |
| 607052 | Scabby Gully | Seven Day Rd | 11 | 1956–74 | 1150 | 132 | 166 | 10 | 1925 | f,m | kj | 3 |
| 607144 | Wilgarup R | Quintarrup | 450 | 1961–86 | 915 | 76 | 865 | 33 | 1925 | f,m | j | |
| 607155 | Dombakup Bk | Malinnup Track | 114 | 1961–82 | 1425 | 387 | 146 | 16 | 1925 | f,m | k | |
| 608001 | Barlee Bk | Upper Iffley | 164 | 1972–82 | 1170 | 154 | 156 | 0 | - | f | j | |
| 608151 | Donnelly R | Strickland Farm | 808 | 1940–86 | 1110 | 176 | 240 | 22 | 1950 | f,m | j | |
| 608171 | Fly Bk | Boat Landing Rd | 67 | 1962–82 | 1415 | 359 | 142 | 25 | 1925 | f,m | kj | |
| 609003 | St Pauls Bk | Cambray | 161 | 1974–82 | 950 | 72 | 194 | 0 | - | f | j | |
| 609005 | Weenup Ck | Mandelup Pool | 87 | 1975–82 | 520 | 27 | 4665 | 85 | 1950 | a,f | mw | |
| 609006 | Weenup Ck | Balgarup | 13 | 1975–82 | 520 | 26 | 6203 | 75 | 1950 | a,f | mw | 1 |
| 610001 | Margaret R | Willmots Farm | 443 | 1970–82 | 1050 | 233 | 200 | 35 | 1925 | f,a | j | |
| 611111 | Thomson Bk | Woodperry Homestead | 102 | 1957–85 | 950 | 125 | 355 | 45 | 1950 | f,a | j | |
| 612001 | Collie R (east) | Coolangata Farm | 1340 | 1968–82 | 720 | 30 | 1625 | 28 | 1970 | f,a | j | 1 |
| 612014 | Bingham R | Palmer | 392 | 1975–82 | 780 | 9 | 387 | 10 | N/a | f,a | j | 2 |
| 612017 | Harris R | Tallanalla Rd | 382 | 1976–82 | 1000 | 45 | 217 | 10 | N/a | f,m | j | 1 |
| 612021 | Bingham R | Stenwood | 50 | 1978–82 | 680 | 7 | 817 | 10 | N/a | f,a | j | 3 |
| 612022 | Brunswick R | Sandalwood | 115 | 1980–82 | 1250 | 260 | 149 | 10 | N/a | f,m | j | |
| 612023 | Lunenburgh R | Silver Springs | 58 | 1980–82 | 1225 | 237 | 206 | 10 | N/a | f,m | j | |
| 612034 | Collie R | South Branch | 668 | 1952–82 | 800 | 45 | 756 | 27 | 1960 | f,m | j | |
| 612230 | Collie R (east) | James Crossing | 169 | 1967–82 | 650 | 39 | 3668 | 61 | 1970 | a,f | jmw | 2 |

## Group II: Tributaries & minor rivers (continued)

| Gauging station number | Stream name | Location name | Area ($km^2$) | Period of record | Long term mean rainfall | Mean runoff (mm) | Mean salinity (mg/L) | Area cleared (%) | Date of major clearing | Land use | Natural vege-tation | Stream gauge status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 613002 | Harvey R | Dingo Rd | 148 | 1970–82 | 1250 | 232 | 118 | 0 | - | f | j | |
| 613004 | Summer Bk | Red Gulch | 7 | 1977–82 | 1180 | 161 | 195 | 5 | N/a | f,p | j | |
| 613005 | Tallanalla Ck | Blackbutt Point | 39 | 1974–82 | 1110 | 124 | 191 | 0 | - | f,p | j | |
| 613006 | Drakes Bk | McLarty Dams | 48 | 1974–82 | 1250 | 212 | 190 | 13 | N/a | f,m | j | |
| 613007 | Bancell's Bk | Waterous | 14 | 1974–82 | 1225 | 282 | 103 | 16 | N/a | f,m | j | |
| 613008 | Falls Bk | Dee Tee 59 | 29 | 1974–82 | 1230 | 309 | 124 | 0 | - | f | j | |
| 613146 | Clarke Bk | Hillview Farm | 17 | 1961–82 | 1200 | 327 | 174 | 10 | 1925 | f,m | j | |
| 614016 | North Dandalup R | Scarp Rd | 153 | 1939–86 | 1300 | 199 | 190 | 0 | - | f | j | |
| 614028 | Dirk Bk | Hopelands Rd | 77 | 1979–82 | 1100 | 150 | 179 | 50 | N/a | m,f | j | |
| 614044 | Yarragil Bk | Yarragil Formation | 73 | 1951–82 | 1075 | 60 | 407 | 0 | - | f,p | j | |
| 614073 | Gooralong Bk | Mundlinup | 51 | 1951–82 | 1225 | 234 | 163 | 10 | N/a | f,m,b | j | |
| 614123 | Chalk Bk | Quindanning Rd | 104 | 1959–82 | 1000 | 82 | 306 | 0 | - | f | j | |
| 614196 | Williams R | Saddleback Rd Bridge | 1440 | 1966–86 | 600 | 47 | 2989 | 90 | 1950 | m,f | mw | |
| 614224 | Hotham R | Marradong Rd Brg | 4020 | 1966–86 | 590 | 26 | 3523 | 85 | 1950 | m,f | wy | |
| 614233 | Little Dandalup R | Scarp Rd | 40 | 1967–82 | 1300 | 214 | 144 | 0 | - | f | j | |
| 615011 | Mooranoppin Creek | Mooranoppin Rock | 83 | 1974–82 | 340 | 3 | 11467 | 88 | 1950 | a,f | ys | |
| 615012 | Avon SE Lks | Kwolyin Hill | 36900 | 1975–82 | 300 | <1 | 35821 | 80 | 1950 | a,f | m | |
| 615013 | Mortlock R | North Frenches | 6870 | 1975–82 | 375 | 2 | 16316 | 95 | 1920 | a,f | t | 3 |
| 615020 | Mortlock R | O'Driscolls Farm | 9560 | 1975–82 | 360 | 1 | 13237 | 95 | 1920 | a,f | ys | |
| 615222 | Dale R (sth) | Jelcobine | 275 | 1966–82 | 540 | 28 | 4878 | 85 | 1920 | a,f | wm | |
| 616001 | Wooroloo Bk | Karl's Branch | 536 | 1962–86 | 850 | 95 | 1810 | 50 | N/a | f,m | j | |
| 616002 | Darkin R | Pine Plantation | 663 | 1968–85 | 700 | 9 | 357 | 5 | N/a | f,p,a | j | |
| 616005 | Wooroloo Bk | Noble Falls | 290 | 1980–82 | 750 | 78 | 2817 | 65 | 1950 | m,f | j | 1 |
| 616006 | Brockman R | Tanamerah | 958 | 1980–82 | 630 | 22 | 2770 | 65 | 1950 | a,f | jmw | 1 |
| 616007 | Rushy Ck | Byfield Rd | 39 | 1969–85 | 950 | 42 | 539 | 5 | N/a | f,p,m | j | |
| 616009 | Pickering Bk | Slavery Lane | 31 | 1969–85 | 1050 | 66 | 165 | 0 | - | f | j | |
| 616010 | Little Darkin R | Hairpin Bend | 40 | 1969–85 | 900 | 30 | 327 | 0 | - | f | j | |
| 616012 | Helena R | Trewd Road | 28 | 1972–82 | 860 | 43 | 916 | 0 | - | f,p | j | |
| 616013 | Helena R | Ngangaguringuring | 329 | 1972–82 | 630 | 7 | 1272 | 8 | N/a | f,p,a | mw | |
| 616014 | Piesse Gully | Furfaro's Orchard | 55 | 1974–82 | 1150 | 146 | 287 | 50 | N/a | f,m | j | |
| 616019 | Brockman R | Yalliawirra | 1510 | 1975–82 | 660 | 23 | 2174 | 65 | N/a | m,f | jmw | |
| 616029 | Stinton's Bk | Moondyne Hollow | 17 | 1977–82 | 1250 | 182 | 286 | 35 | N/a | f,m | j | |
| 616065 | Canning R | Glen Eagle | 544 | 1950–82 | 890 | 42 | 323 | 0 | - | f | j | |
| 616165 | Lennards Bk | Molecap Hill | 62 | 1962–82 | 725 | 90 | 328 | 60 | N/a | a,f | lw | |
| 616178 | Jane Bk | National Park | 73 | 1963–82 | 1020 | 207 | 503 | 50 | N/a | f,m | j | |
| 616189 | Ellen Bk | Railway Parade | 590 | 1965–82 | 775 | 53 | 596 | 65 | 1950 | m,f | lw | |
| 617001 | Moore R | Quinns Ford | 12400 | 1969–82 | 500 | 4 | 7429 | 85 | N/a | a,f | sh | |
| 617002 | Hill R | Hill River Springs | 692 | 1971–82 | 580 | 44 | 490 | 70 | 1950 | a,f | sh | |
| 617058 | Gingin Bk | Gingin | 120 | 1957–82 | 720 | 118 | 311 | 80 | 1950 | m,f | xw | |

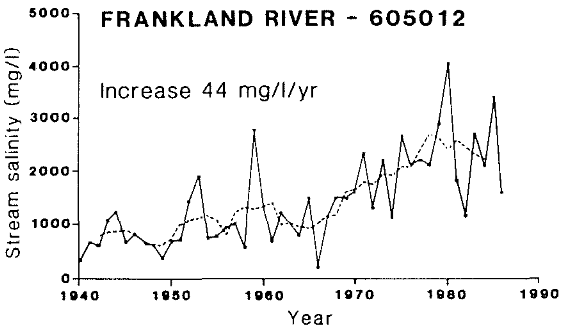
## **Group III: Coastal rivers** (Excludes catchments where gauging commenced after 1980)

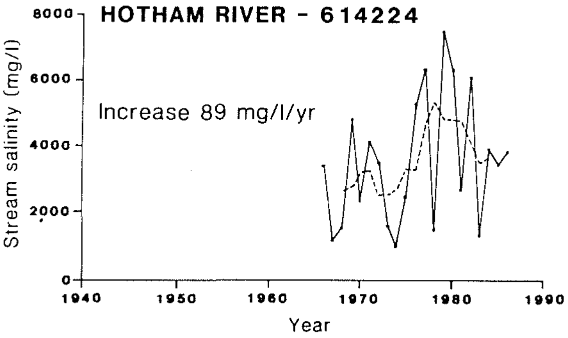
| Gauging station number | Stream name | Location name | Area (km²) | Period of record | Long term mean rainfall | Mean runoff (mm) | Mean salinity (mg/L) | Area cleared (%) | Date of major clearing | Land use | Natural vege-tation | Stream gauge status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 602031 | Waychinicup Ck | Cheynes Beach Rd | 156 | 1969–82 | 720 | 60 | 718 | 45 | 1950 | n,a | mjs | |
| 602041 | Limeburners Ck | | 7.3 | 1954–63 | 900 | 73 | 279 | 0 | - | n | h | |
| 602187 | Angove Ck | Pumping Station | 29 | 1963–82 | 770 | 65 | 346 | 30 | N/a | n,a | lw | |
| 602188 | King Ck | Fishermans Rd | 17 | 1963–78 | 770 | 118 | 596 | 70 | N/a | a,n | lw | |
| 602199 | Goodga R | Black Cat | 46 | 1964–82 | 800 | 85 | 422 | 55 | N/a | a,n | lw | |
| 603001 | Marbellup Bk | Elleker | 117 | 1971–82 | 920 | 133 | 362 | 65 | 1950 | a,m | j | |
| 609002 | Scott R | Brennans Ford | 645 | 1969–82 | 1100 | 161 | 215 | 30 | 1950 | f,a | j | |
| 610003 | Vasse R | Chapman Hill | 53 | 1972–82 | 1000 | 196 | 197 | 85 | 1925 | a,f | j | |
| 610005 | Ludlow R | Happy Valley | 108 | 1973–82 | 925 | 59 | 185 | 0 | - | f,p | j | |

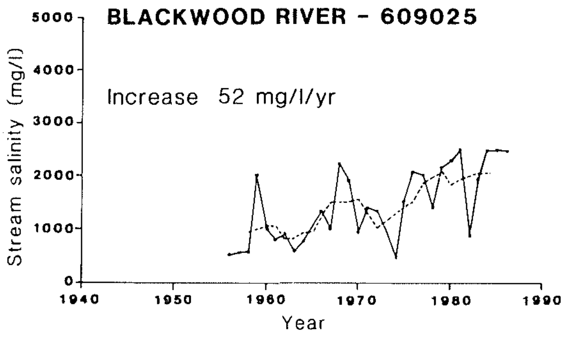
## **Group IV: Research streams** (Excludes catchments where gauging commenced after 1980)

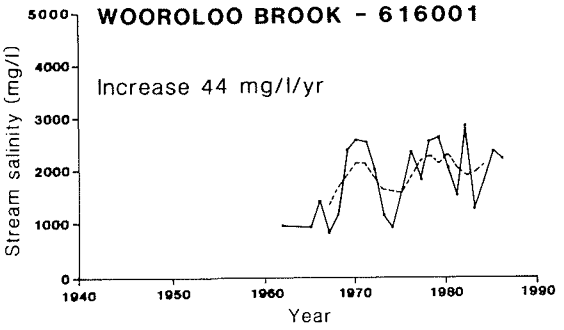
| Gauging station number | Stream name | Location name | Area (km²) | Period of record | Long term mean rainfall | Mean runoff (mm) | Mean salinity (mg/L) | Area cleared (%) | Date of major clearing | Land use | Natural vege-tation | Stream gauge status |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 607005 | Yerraminnup Ck | North Catchment | 2.4 | 1975–86 | 850 | 19 | 265 | 0 | - | f | j | |
| 607012 | Trib Quininup Bk | April Rd South | 2.1 | 1976–86 | 1070 | 87 | 125 | 0 | - | f | j | |
| 608004 | Trib Easter Bk | Lewin North | 1.2 | 1976–86 | 1220 | 191 | 109 | 0 | - | f | j | |
| 609004 | St Pauls Bk | Dido Rd | 25 | 1974–82 | 930 | 59 | 173 | 0 | - | f | j | |
| 609008 | Apostle Bk | Mill Brook | 26 | 1976–82 | 920 | 97 | 174 | 0 | - | f | j | |
| 610007 | Ludlow R | Claymore | 10 | 1977–82 | 950 | 18 | 235 | 0 | - | f | j | |
| 610008 | Margaret R | N Br Whicher Range | 15 | 1977–82 | 930 | 64 | 201 | 0 | - | f | j | |
| 612008 | Bingham R Trib | Ernie's | 2.7 | 1974–82 | 710 | 11 | 88 | 0 | - | f | j | |
| 612011 | Salmon Bk | Salmon | 0.82 | 1974–82 | 1200 | 113 | 257 | 0 | - | f | j | |
| 614007 | South Dandalup Trib | Del Park | 1.3 | 1974–82 | 1300 | 156 | 133 | 0 | - | f,b | j | |
| 614011 | Mooradung Bk Trib | Tunnel Rd | 2.1 | 1975–82 | 730 | <1 | 337 | 0 | - | f | j | |
| 614017 | Little Dandalup Trib | Warren Bk | 0.85 | 1977–82 | 1300 | 140 | 125 | 0 | - | f,b | j | |
| 614018 | Little Dandalup Trib | Bennett | 0.85 | 1977–82 | 1300 | 178 | 95 | 0 | - | f,b | j | |
| 614019 | Little Dandalup Trib | Hansen | 0.85 | 1977–82 | 1300 | 47 | 115 | 0 | - | f | j | |
| 614020 | Little Dandalup Trib | Higgins | 0.71 | 1977–82 | 1300 | 16 | 124 | 0 | - | f | j | |
| 614021 | Wilson Bk Trib | Lewis | 1.7 | 1977–82 | 1300 | 69 | 111 | 0 | - | f | j | |
| 614022 | North Dandalup Trib | Jones Bk | 1.7 | 1977–82 | 1300 | 5 | 143 | 0 | - | f | j | |
| 614046 | Yarragil Bk Trib | Yarragil North | 2.23 | 1984–82 | 1050 | 2 | 140 | 0 | - | f | j | |
| 614048 | Yarragil Bk Trib | Yarragil 4x | 2.58 | 1984–86 | 1070 | 16 | 447 | 0 | - | f | j | |
| 614049 | Yarragil Bk Trib | Yarragil 6c | 4.58 | 1984–86 | 1050 | 9 | 382 | 0 | - | f | j | |
| 614050 | Yarragil Bk Trib | Yarragil East | 5.01 | 1984–86 | 1050 | 12 | 180 | 0 | - | f | j | |
| 616016 | Helena R Trib | Wellbucket Road | 4.7 | 1974–83 | 690 | 2 | 70 | 0 | - | f | j | |
| 616023 | Waterfall Gully | Mount Curtis | 8.7 | 1966–82 | 1275 | 283 | 142 | 0 | - | f | j | |

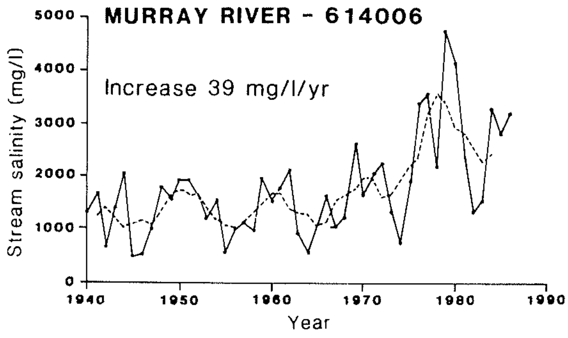
# *Appendix B: Stream Salinity Trends of Some Salinity Hazard Group 4 Catchments (see Table 13)*

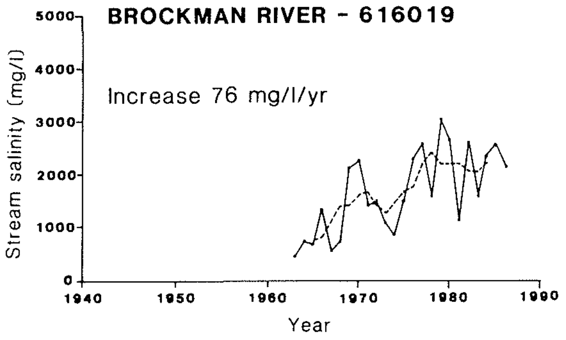


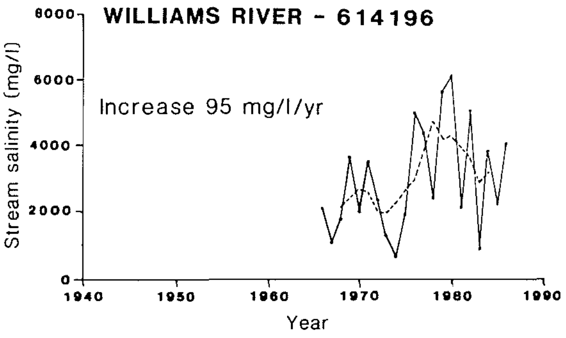












**Key to graphs**

——— Annual

— — — Five year moving average

# *Appendix C: Members of the Steering Committee for Research on Land Use and Water Supply*

| | |
|---|---|
| **Chairman** | |
| Mr K. Barrett | Water Authority of Western Australia |
| **Members** | |
| Dr A. Allen | Geological Survey, Mines Department |
| Dr C. Barber | CSIRO |
| Mr J. Bartle | Department of Conservation and Land Management |
| Mr J. Blyth | Department of Conservation and Land Management |
| Dr P. Christensen | Department of Conservation and Land Management |
| Dr J. Fox | Curtin University of Technology |
| Dr Goen Ho | Murdoch University |
| Dr F. Hingston | CSIRO |
| Dr C. John | Worsley Alumina Pty Ltd |
| Mr I. Loh | Water Authority of Western Australia |
| Dr R. Nulsen | Department of Agriculture |
| Mr N. Orr | Environmental Protection Authority of Western Australia |
| Dr N. Schofield | Water Authority of Western Australia |
| Mr G. Slessar | Alcoa of Australia Pty Ltd |
| Mr H. Ventriss | Water Authority of Western Australia |
| Vacant | University of Western Australia |
| **Secretary** | |
| Mrs T. Berson | Office of the Minister of Environment (W.A.) |

# *Appendix D:* ***Members of the Water Resources Catchments Rehabilitation Subcommittee*** *(of the Steering Committee for Research on Land Use and Water Supply)*

**Convener**

| | |
|---|---|
| Mr I. Loh | Water Authority of Western Australia |

**Members**

| | |
|---|---|
| Mr G. Anderson | CSIRO |
| Dr B. Anson | Water Authority of Western Australia |
| Mr J. Bartle | Department of Conservation and Land Management |
| Mr M. Martin | Geological Survey of Western Australia |
| Mr R. Moore | Department of Conservation and Land Management |
| Mr P. Ritson | Water Authority of Western Australia |
| Dr N. Schofield | Water Authority of Western Australia |
| Mr P. Scott | Department of Agriculture |
| Mr D. Williamson | CSIRO |

# Glossary

| | |
|---|---|
| Adsorption | The condensation (collection) of a gas, liquid, or dissolved substance onto the surface of a solid. There may or may not be a chemical reaction between the substance adsorbed and the surface of the solid. |
| Alienation (of land) | The process of opening up Crown land for private ownership. |
| Brackish water | Water with salinity greater than 1500 mg/L TSS *or* 600 mg/L chloride but less than 5000 mg/L TSS. |
| Brine | A solution containing a higher proportion of common salt than seawater. |
| Bulge profile | A soil profile which has a maximum salinity at an intermediate depth in the profile. |
| Calibration (of a model) | The procedure of modifying model parameters so that output from the model is a best fit to measured observations, usually over some limited calibration period. |
| Capillary gradient | The gradient of negative pressure potential resulting from the capillary and adsorptive forces due to the soil matrix. |
| Clearing control | Term used to describe the legal and adminstrative procedures associated with the Country Areas Water Supply Act (1947–76) which control clearing of native vegetation through a licensing system. |
| Constrained water resources | Water resources not currently accessible for development for environmental or legal reasons. |
| Convection (of solutes) | The mass flow of the soil solution. |
| Divertible water resources | The average annual volume of water which, using current practice, could be removed from developed or potential surface water or groundwater sources on a sustained basis at rates capable of serving urban, irrigation, industrial or extensive stock uses. It does not include low yielding bores in fractured rock aquifers providing domestic or stock supplies by low yielding pumps such as windmills or surface water sources such as roof runoff or small farm dams. |
| Dry fallout | Salt deposited on the landscape not falling as dissolved salts in rainfall. |
| Duricrust | A firmly cemented material often occurring below the soil surface, but in some cases as outcrops. It is primarily composed of oxides of iron and aluminium, but sometimes includes soils and weathered rock. It has variations in fabric; in some cases it consists of cemented pisolites, while in others it appears as soil material which has been impregnated and indurated by oxides. The material often has voids and channels. Where the cemented pisolitic type and the indurated soil type occur together, the former is stratigraphically higher. Duricrust sometimes includes sand and water-worn pebbles. |
| Electrical conductivity (EC) | The ability of a soil mass, water sample or solution of water extract to conduct electricity. Strongly correlated to the quantity of ions in the soil or in solution. |

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| Exchange (cation) | The chemical replacement of cations within the soil. |
| Grain per gallon | Imperial measure of solute in solution (equivalent to 14.2 mg/L). |
| Groundwater | Water in the soil or subsoil of sufficient volumetric water content (usually saturated) to move in response to gravity and hydraulic pressure gradients. |
| Hydraulic gradient | The gradient of soil water pressure or tension in a soil. |
| Hydrodynamic dispersion | The dispersion of solutes during flow due to different flow velocities through the pore space. |
| Interception | Water retained for some period, however short, after rain has struck the vegetation above the mineral soil surface. |
| Ion | An electrically charged atom or group of atoms. |
| Isohyet | A line on a map joining places of equal rainfall amount. |
| Laterite | A residual material formed through the prolonged weathering of rocks, under warm humid conditions, though with a marked dry season. Generally high in iron and aluminium oxides and silica. |
| Marginal water | Water with salinity greater than 500 mg/L TSS but less than 1500 mg/L TSS *or* less than 600 mg/L chloride. |
| Molecular diffusion | The movement of solutes due to a concentration gradient within the solution. |
| Monotonic profile | A soil profile in which salt content increases uniformly with depth. |
| Mottled zone | A zone which occurs below the gravel or duricrust zone, and is in sharp contrast to them. Commonly it has clay or clay loam texture and, other than quartz, minerals are not recognizable to the eye. The main feature of this layer is the variation of colour which includes white, grey, yellow-brown and red mixed in various proportions. At the base of the mottled zone the material is less coloured. |
| Multi-port piezometer | A single bore with a series of tubes measuring the groundwater pressure at different depths beneath the water table. |
| Pallid zone | A zone which generally occurs below the mottled zone, but may extend directly below the gravel or duricrust zone. The pallid zone is predominantly white or light grey in colour, clay loam in texture, and has recognizable weathered minerals other than quartz. Thus it is possible to see weathered felspar crystals and, when ferro-magnesian minerals are present, there may be finely coloured patches. |
| Parametric model | A series of equations or algorithms that define the output of the model from its input and which are characterised by 'parameters' or 'coefficients' that affect the model response. In this report it generally relates to models that simulate the conversion of input rainfall and evaporation demand to the outputs of streamflow and evapotranspiration. |

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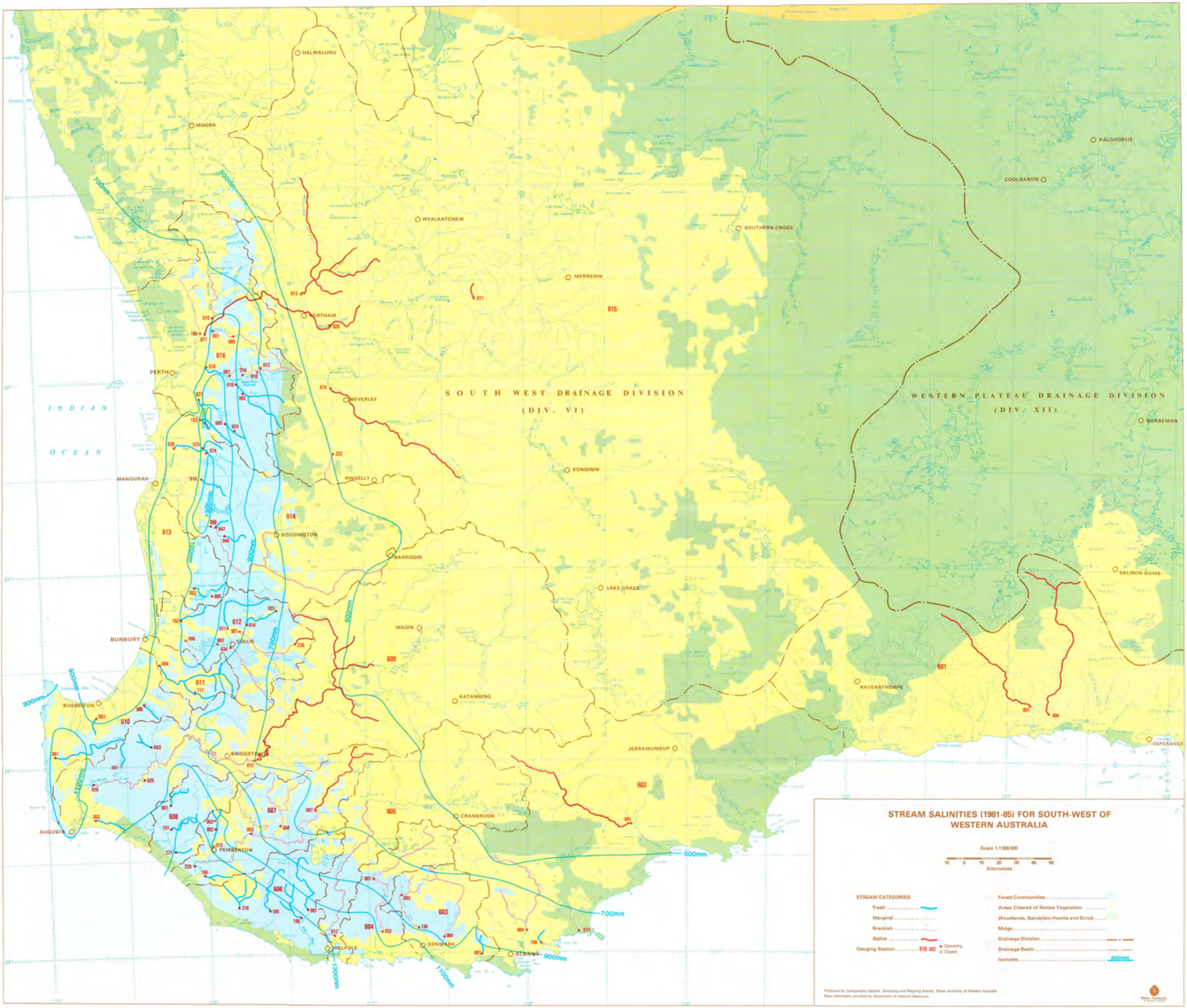
| Percolation | The passage of water under hydrostatic pressure through the interstices of a soil or rock, excluding the movement through large openings. |
| Piezometer | A small diameter bore designed for monitoring water table levels or hydraulic pressure heads and for water quality sampling. |
| Potable water | Water suitable for human consumption. |
| Precipitation | The deposition of water in a solid or liquid form on the Earth's surface from atmospheric sources. |
| Preferred pathways | Pathways such as root channels in which water can move rapidly through a soil without passing through the soil matrix. |
| Reforestation | Planting trees as a forest on land previously cleared of native forest overstorey. |
| Resumption | Compulsory aquisition of private land by Government. |
| Ring-barking | Killing trees by cutting all active pathways for sap movement around the circumference of the trunk. |
| Saline water | Water with salinity greater than 5000 mg/L TSS. |
| Salinisation | The process of salt accumulation in soil or in water. |
| Salinity | The degree to which water contains dissolved salts. |
| Saprolite | Residual material resulting from the in situ weathering of bedrock. |
| Saturated zone | That part of the soil in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric. |
| Throughflow | Downslope flow of water occurring physically within the soil profile, under saturated or unsaturated conditions. |
| Transpiration | The process by which water in plants is transferred to the atmosphere as water vapour. |
| Unsaturated zone | That part of the soil profile between the land surface and the water table. It includes the capillary fringe. In this zone liquid water is under less than atmospheric pressure while water in the gas phase is at atmospheric pressure. |
| Water flux density | The rate of flow of water per unit cross-sectional area perpendicular to the direction of flow. |
| Weathering zone | A zone which extends below the pallid zone and is transitional to the unweathered rock below. In this material crystals of different minerals are clearly visible and bands of different composition are evident; it has the appearance of rock, but not the hardness. Normally it can be crushed between the fingers and may have a sandy loam texture. |
| Wetland | Areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline, e.g., waterlogged soils, ponds, billabongs, lakes, swamps, tidal flats, estuaries, rivers and their tributaries. |



## STREAM SALINITIES (1981-85) FOR SOUTH-WEST OF WESTERN AUSTRALIA

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