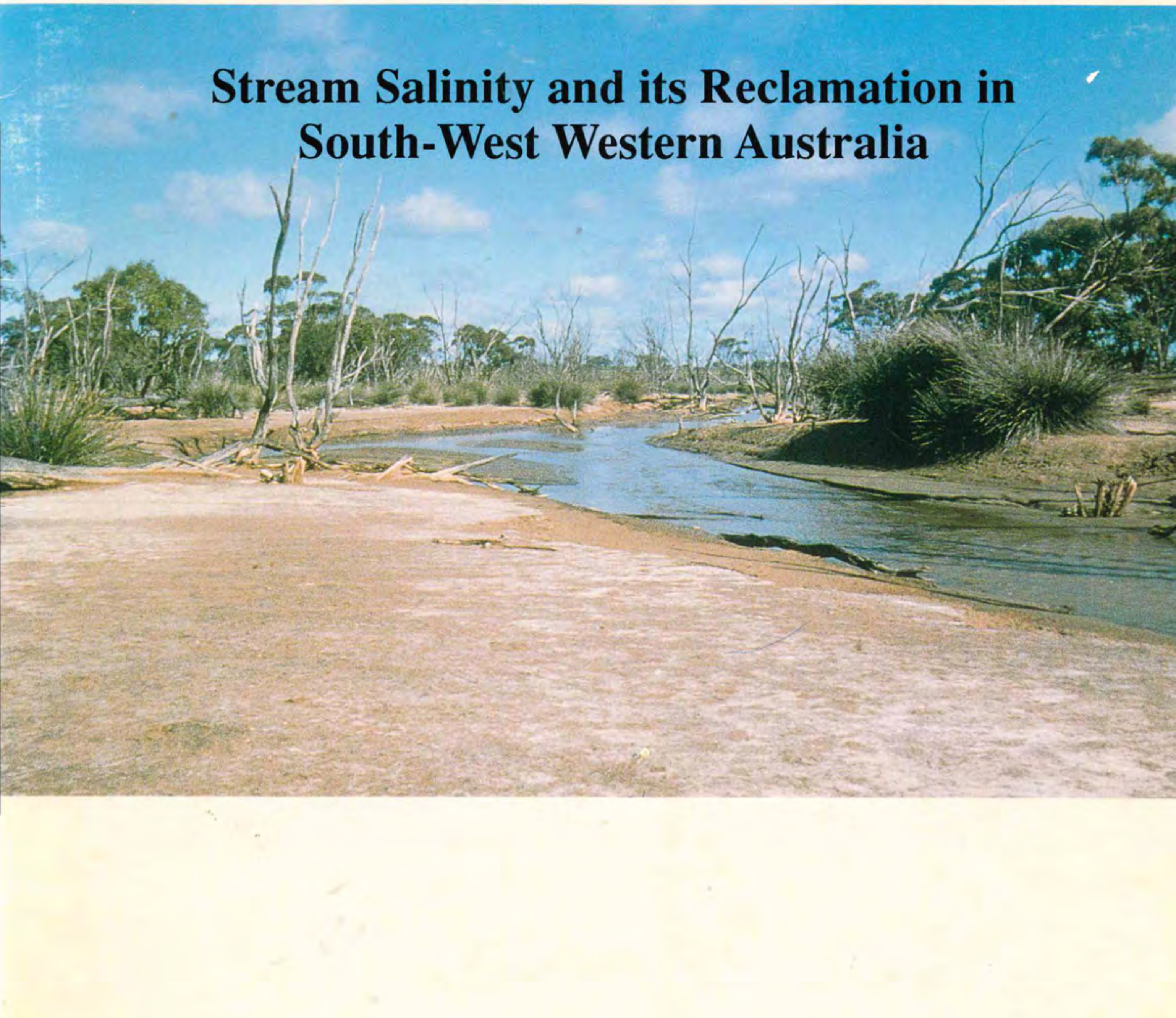
Stream Salinity and its Reclamation in South-West Western Australia



Steering Committee for Research on
Land Use and Water Supply

Stream Salinity and its Reclamation in South-West Western Australia

Report of the Steering Committee for Research on Land Use and Water Supply

Water Authority of Western Australia
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Streamline Abstract

STREAM SALINITY AND ITS RECLAMATION IN SOUTH-WEST WESTERN AUSTRALIA

Steering Committee for Research on Land Use and Water Supply (Western Australia)

This report gives a brief but comprehensive review of stream salinity development and vegetative reclamation measures in south-west Western Australia. The first part of the report deals with the history, mechanisms, regional impact and trends of agriculturally-induced stream salinity. This is followed by an assessment of reforestation and agricultural strategies to control stream salinity. The report concludes with an identification of management issues and gives directions of future research and recommendations for action.

Key words : Stream salinity, water resources, reforestation, reclamation, vegetation, agriculture, timber, pulpwood, salinity management, conservation, groundwater, catchment, review.

Water Authority of Western Australia, Perth 1989, ISBN 0 7309 1799 1

Other Recent Reviews for 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 & 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.
4. *The Impact of Agricultural Development on the Salinity of Surface Water Resources of South-West Western Australia.* Water Authority of Western Australia, Report No. WS 27, 83 pp, August 1988.
5. *Vegetation Strategies to Reduce Stream Salinities of Water Resource Catchments in South-West Western Australia.* Water Authority of Western Australia, Report No. WS 33, 98 pp, July 1989.

Foreword

Stream salinity and land salinisation are serious, inter-related, environmental and resource problems. The impact on water resources has been particularly severe. Currently over half of the divertable surface water resources of south-west Western Australia are no longer fresh.

When this region was naturally vegetated, all rivers flowed fresh. Salinisation developed insidiously as European settlers progressively cleared land for farming. Early impacts were localised with water from individual farm and railway dams becoming brackish, then saline, following clearing of their catchments. By the 1920's, inquisitive scientists and engineers had gained a qualitative understanding of the cause of stream salinity. Unfortunately, this knowledge was not nurtured to influence future land use planning.

Land salinisation and clearing continued to increase in rate and extent, particularly after 1950. Lacking convincing knowledge that only research and monitoring can provide, significant agricultural expansion continued within some existing and future water supply catchments. The marked increase in salinity of recent years is the legacy of this land development two and three decades ago.

Reliable stream flow and salinity monitoring was progressively established from 1965 with detailed hydrologic research commencing in the mid-1970s. The complexity and seriousness of salinity was recognised and the challenge accepted by research and land management groups within State Government Departments, CSIRO, Tertiary Institutions and private enterprise. Research has been multidisciplinary, innovative and well co-ordinated. It includes some of the earliest reforestation research in Australia.

Growing in stature and importance through the years, this monitoring and research has progressively provided knowledge essential to the development of improved land management strategies and actions. The challenge now is to restore water quality while maintaining or enhancing economic productivity of the land. Ongoing development of the south-west is further increasing the value of fresh water as a resource for development and for the natural environment. Research teams, land and water managers, landowners and local communities are now combining their efforts in tackling land and stream salinity.

This long awaited review of stream salinity and its reclamation is based on two technical reports recently published by the Steering Committee: 'The Impact of Agricultural Development on the Salinity of Surface Water Resources of South-West Western Australia' and 'Vegetation Strategies to Reduce Stream Salinities of Water Resource Catchments in South-West Western Australia'. The many contributors to these reports and to our understanding of salinity are gratefully acknowledged. We must build on this knowledge base and improve water quality for the benefit of present and future generations.

K L Barrett

K L Barrett

Chairman, Steering Committee for Research on Land Use and Water Supply

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Acknowledgements

The Steering Committee (Appendix II) extends its thanks to the many people from various organisations and disciplines who have contributed over the years to the knowledge of the salinity problem and to the development of reclamation measures.

Members of the Water Resources Catchments Rehabilitation subcommittee of the Steering Committee are thanked for their extensive technical reviewing of this report and the two companion detailed reports on which this report is based.

The Steering Committee is indebted to Dr N.J. Schofield for writing this report.

Executive Summary and Recommendations

INTRODUCTION

This report describes one of Western Australia's most serious environmental and resource problems - salinisation of its streams. Following extensive and ongoing research, we are now able to adequately explain the causes and mechanisms of stream salinisation and, more importantly, implement measures for their reclamation. **This review presents the current status of knowledge and identifies future research and management requirements.**

CAUSES OF STREAM SALINITY

It is now widely accepted that stream salinisation in Western Australia has resulted directly from clearing native vegetation for the development of agriculture. Traditional agricultural pastures and crops have lower annual water use than native vegetation. This results in a higher proportion of rainfall recharging groundwater. **Groundwater levels consequently have risen following clearing, bringing large quantities of previously 'stored' salt to the soil surface and streams.** This problem is particularly severe for the medium and lower rainfall areas (less than 900 millimetres per year) of the south-west which are now predominantly under agricultural use.

REGIONAL IMPACT OF AGRICULTURAL DEVELOPMENT ON STREAM SALINITY

Streams whose catchments lie wholly above 1100 millimetres per year (mm/yr) rainfall are essentially free of significant salinity risk despite the land use, although they may experience some increase in their salinity following forest clearing. **Streams with catchments which extend inland to areas of below 1100 mm/yr rainfall are at risk of salinisation**, the risk increasing the further inland the catchment extends.

Historically the high rainfall areas have remained largely under native forest because the soils were too poor for agricultural use. These areas provide the bulk of the current surface water supplies to the south-west. Although these river catchments are not large in area, their water yields are high due to high rainfall. Clearing and other activities in these areas are now closely controlled. **Nearly 50% of the water resources of the south-west are fresh and protected by forest.**

The major rivers and largest water resources of the south-west (i.e. the Avon, Murray and Blackwood) now have high salinities rendering them unsuitable for domestic water supply. The catchments of these rivers extend well into the low rainfall areas in which they are extensively cleared.

There is an intermediate group of rivers whose catchments have been less extensively cleared in their lower rainfall regions. These rivers typically have salinities in or close to drinkable levels but require active management to maintain or reclaim their water resource value. Included in this group are the Helena River (Mundaring Weir catchment), Collie River (Wellington Dam catchment), Denmark River and Warren River.

SALINITY TRENDS

Stream salinities of fully forested catchments have been declining over the last two decades, probably in response to lower rainfall conditions which have led to decreased groundwater levels and presumably less groundwater salt discharge to streams.

In contrast **all rivers with partially cleared catchments in lower rainfall areas have increasing salinity**. The rate of salinity increase is higher the lower the rainfall. **Stream salinity increases have accelerated over the last 20 years.**

Stream salinities cannot continue increasing in the long term. In agricultural areas salt export from the landscape is considerably greater than salt input in rainfall. Thus salt stored in the soil is slowly being leached from the land. For the 600 to 900 mm rainfall areas, groundwater simulation studies suggest that **stream salinities will continue to increase for another 20 to 50 years** before reductions caused by salt leaching commence.

STREAM SALINITY MANAGEMENT

Salinity management of south-west catchments is based on soil salt storage and degree of agricultural clearing.

Forested catchments with significant salt storage are managed with a policy of high protection of water quality. The effects of activities such as bauxite mining, forest logging, thinning and clearfelling, and natural disturbances such as forest diseases and pests are intensively researched.

High salt storage catchments with some lower rainfall areas cleared, and with marginal but increasing salinity, have been the focus of considerable attention over the last 30 years. Legislative actions to control the release of Crown land and to control clearing of native forest on these catchments, which are important water resources, were implemented between 1961 and 1978. Despite these legislative actions, which were an essential first step, stream salinities have continued to increase at an alarming rate due to the earlier clearing. Further supplementary management was clearly required. The most promising approach is reforestation which was initiated in the Collie catchment in 1979.

The extensively and totally cleared catchments, which include some of the major water resources of the south-west, are not currently cost-effective to rehabilitate for water supplies, although tributaries in their high rainfall forested areas could be developed.

REFORESTATION STRATEGIES

Reforestation is considered to be the most cost-effective and environmentally acceptable method of reclaiming high salinity streams in water resource catchments. Since reforestation stands can be designed to consume more water per unit area than the original native vegetation, **it is generally necessary to reforest only part of the agricultural land.** The main design parameters for reforestation are tree selection, planting density and planting location.

The principal criteria in tree selection are adaptation to the environment, high annual water use and multiple use. A wide range of species have been identified which are adapted to well-drained soils distant from saline seeps. Several of these have commercial potential for timber and pulpwood production. In contrast **only a few species are known which are adapted to saline seep conditions** (waterlogging and high salinity). Techniques such as double ridge mounding are currently being researched to improve the establishment of trees in saline seeps. At present **there are not adequate data to confidently rank adapted species on the basis of their water use,** and this criterion is not extensively used.

The other reforestation design criteria of planting density and location have given rise to several possible reforestation strategies. **Four such strategies have been investigated in Western Australia: (A) lower slope and discharge zone planting, (B) wide-spaced plantations covering most of the cleared area, (C) strips or small blocks strategically placed but covering a small proportion of the cleared area, and (D) dense plantations covering a high proportion of the cleared area.** Most of the research has focused on the effect of reforestation on groundwater, although there are some data on streamflow, stream salinity and stream salt discharge.

The response of groundwater levels beneath reforestation was found to depend primarily on area planted and crown cover. Relative to groundwater levels beneath pasture, **groundwater levels beneath reforestation decreased proportionately with area planted** (for similar crown covers) **and with total tree cover** (as represented by the product of area planted and crown cover). Generally groundwater levels began to decline beneath reforestation relative to pasture three to four years after planting. **The strategy with low percentage planting (C) had little effect on groundwater level** and would not be recommended in this rainfall zone (600-900 mm/yr). **The strategy with high percentage planting in dense stands (D) achieved groundwater level reductions of the order of five metres over nine years.** However rainfall was 10% below average and smaller reductions would be expected in average rainfall conditions.

Groundwater salinities beneath the experimental reforestation stands declined on average by about 10% over seven years in the 600-900 mm/yr rainfall zone. At one site further east (~ 500 mm/yr rainfall) groundwater salinities were found to increase.

Stream data are only currently available for one small catchment. This catchment (880 mm/yr rainfall)had extensive areas of agricultural land which were totally re-forested except for the valley floor. Over a period of nine years streamflow volumes and salt discharge decreased by nearly 90% while stream salinity rose slightly. This implies that **for large water resource catchments, reforestation of the high salt exporting low rainfall areas would significantly reduce the stream salinity at the catchment outlet.**

AGRICULTURAL STRATEGIES

Since the partial reforestation strategies aim to leave significant areas of cleared land under agriculture, it is sensible to develop agricultural practices which increase water use and/or decrease groundwater recharge. **Four strategies have been investigated: agronomic manipulation, fodder crop trees, surface drainage and re-vegetation of saline seeps.**

Agronomic manipulation involves the selection, establishment and management of higher water using species. **Annual crops of lupins, oats, rape and barley, and perennial pastures such as lucerne and phalaris have all been found to transpire more than traditional, annual, clover-based pastures.**

There is evidence that perennial, deep-rooting fodder crop trees and shrubs have higher water use than annual pastures, although there has been little research in this area. One promising species, Tagasaste, appears to be more profitable than annual pastures when grown on deep infertile sands.

Shallow surface drains and underground pipe drains, when well designed and constructed, can be effective in removing perched water from seasonally water-logged areas. This results in increased crop yield and transpiration and decreased groundwater recharge.

Revegetation of saline seeps with halophytic fodder shrubs for sheep grazing has proven to be an economically viable approach in lower rainfall agricultural areas. These shrubs, however, may be adversely affected by the more prolonged waterlogging that occurs on seeps in the higher rainfall water resource catchments. In these areas reforestation is the predominant strategy, although **there is potential for the use of halophytic shrubs where site conditions are too severe for trees to establish.**

INTEGRATED CATCHMENT MANAGEMENT

An integrated catchment management approach has been adopted by the Western Australian government to control stream salinity whilst simultaneously maximising land productivity, conservation and recreation values. This approach requires land and water management agencies to develop integrated farm, catchment and regional plans and fosters the co-operation and resources of landowners and local communities. At present integrated catchment management is being evaluated on the Denmark River catchment.

MANAGEMENT ISSUES

Clarification of the salinity management priorities of catchments is required. The Collie and Denmark River catchments have already been identified as high priority. A long term State salinity strategy should be developed to propose appropriate levels and types of management for all salt-affected streams.

Integrated catchment management systems should be developed and promoted. This will involve a more systematic approach to managing land use to meet specified goals of water quality, land productivity and conservation and recreation values. A suite of forestry and agricultural strategies should be further developed and matched to measured land capability.

The development of commercial tree cropping on farmland has considerable potential to augment salinity control measures. To achieve salinity control it is essential that commercial tree plantations be directed to areas below 900 mm/yr rainfall. Also, to maximise their effectiveness, plantations should be topographically located according to reforestation guidelines being developed in integrated catchment management.

A policy for remnant native vegetation on farmland requires rapid development. In areas of stream salinity protection or reclamation, remnant vegetation should be protected and managed.

The impact of salinity on conservation of lake and riverine ecosystems requires further assessment followed by the development **and implementation of management strategies.** The ecological importance of the few remaining fresh inland wetlands deserves high management priority.

Protection of high salt storage catchments in State forest should not be overlooked. Multiple use of these forests in terms of mining and forest operations, and the continuing escalation of forest diseases and pests requires careful research and management.

CONCLUSIONS

- **Agricultural clearing has led to the development of extensive stream salinisation in south-west Western Australia.**
- **Streams with catchments located wholly in high rainfall areas (greater than 1100 mm/yr) will remain fresh even with forest clearing, although some salinity increase is likely to occur.**

- Streams of fully forested catchments extending to lower rainfall areas have high salinity risk but will remain fresh provided the forest is protected. The salinities of these streams have decreased over the last two decades.
- Streams whose catchments have been subject to agricultural clearing in lower rainfall areas (lower than 900 mm/yr) have rapidly increasing salinities.
- Stream salinities are higher the lower the average catchment rainfall and the higher the proportion of catchment cleared.
- Land alienation and clearing controls have significantly limited but not halted stream salinity increases. Without restorative action, stream salinities will continue to increase for another 20-50 years in the 600-900 mm rainfall zone.
- Reforestation strategies with moderate to high proportions of cleared area replanted have been successful in lowering groundwater levels beneath the reforestation in the critical 600-900 mm/yr rainfall zone within ten years of planting.
- The rate of groundwater level reduction is proportional to the total reforestation tree cover on the cleared area.
- To eliminate salt discharge to streams via groundwater it is necessary to have some discharge zone reforestation in the revegetation strategy. Specialised tree selection and establishment procedures are required for the discharge (seep) zone.
- Groundwater salinity beneath reforestation has decreased at most sites in seven years since planting.
- Salt discharge from a small catchment was dramatically reduced following almost complete reforestation.
- Tree selection for reforestation should be based firstly on adaptation to the specific environment and secondly on multiple use.
- Agricultural strategies including agronomic manipulation, fodder crop trees, halophytic fodder shrubs and correctly designed drainage all have potential for ameliorating salinity problems.
- Commercial tree planting has the potential to accelerate the rate of reforestation for salinity control.
- Integrated catchment management is the best approach to future catchment rehabilitation.

RECOMMENDATIONS

1. New research is essential on:
    - the development of integrated catchment management systems and analysis of their hydrologic, economic and social implications;
    - the potential impacts of the Greenhouse Effect on stream salinisation and its reclamation;
    - the impact of salinity on the conservation values of the few remaining freshwater lakes in low rainfall agricultural areas, and the development of reclamation methods.

2. The following current research programmes should be significantly upgraded:

   - the development of models which can predict future stream salinities with and without reforestation;
   - revegetation water use studies in both seep and non-seep areas;
   - incorporation of perennial pastures into current farming systems;
   - the potential of a wide range of fodder crop trees to ameliorate salinity problems;
   - evaluation and extension of the hydrological effectiveness of wide-spaced tree planting strategies (agroforestry).

3. The following current research programmes should be continued:

   - research to improve tree selection, breeding and establishment in and adjacent to saline seeps;
   - evaluations of a range of reforestation strategies in terms of hydrologic response, productivity and economic performance;
   - measurement of the effects of reforestation on stream salinity, streamflow and salt discharge from small to large catchments;
   - study of salt dynamics beneath reforestation stands;
   - studies of water and salt dynamics in experimental catchments cleared for agriculture;
   - investigation of broad-scale survey methods to identify high recharge areas.

4. New research would be desirable to determine:

   - the wider benefits of tree planting programmes;
   - alternative strategies (other than vegetation) to control stream salinisation.

5. Management issues that should be addressed are:

   - clarification of the salinity management priorities of catchments;
   - development and promotion of integrated catchment management;
   - promotion of commerical tree croping on farmland for salinity control;
   - development and implementation of management strategies to conserve or reclaim valuable lake and riverine ecosystems affected by salinity;
   - policy development for the management of remnant native vegetation within the integrated catchment management framework.

6. A long-term salinity control strategy should be developed for the State.

1. 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 provides a comprehensive summary of both the impact of agricultural clearing on stream salinity, and reforestation and agricultural strategies to reclaim stream salinity. The first part of the report briefly deals with the history, causes, regional impact and trends of agriculturally-induced stream salinity. This is followed by an assessment of reforestation and agricultural strategies to reclaim stream salinity. The report concludes with an identification of current management issues, future research requirements and general conclusions. Recommendations for action are presented in the Executive Summary. The content of this report is based on two detailed technical reviews (Schofield *et al.*, 1988, 1989).

2. History of Salinity Development and Management

Since settlement of Western Australia by Europeans in 1829, the economy of the State has relied heavily on agriculture. Agricultural growth was slow to 1900, but expanded rapidly 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 unforeseen by the settlers. Groundwater rose beneath the pastures and crops 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 basic mechanisms were fairly well understood by the 1920s (Bleazby, 1917; Wood, 1924).

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 (Sadler and Cox, 1987). 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.

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 led to the government progressively introducing controls on land alienation (release of Crown Land for private ownership) and clearing. 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 catchment in 1976, and the Mundaring, Denmark, Warren and Kent catchments in 1978. These actions were accompanied by the initiation of an extensive research programme to gain a detailed understanding of the salinity problem and develop methods of stream and land salinity reclamation.

3. *Causes of Stream Salinity*

It is now well established that stream solutes in the south-west are transported from the ocean to the land via rainfall. As with the ocean, the main component of stream solutes is sodium chloride, being about 80% by weight. Geographic studies of atmospheric solute deposition in the south-west have shown that chloride concentration in rainfall and chloride precipitation decrease with increasing distance from the coast (Figure 1) (Hingston and Gailitis, 1976). Rainfall salinities are typically of the order of 10–20 milligrams per litre (mg/L) Total Soluble Salts (TSS) in the water resource catchments of the south-west.

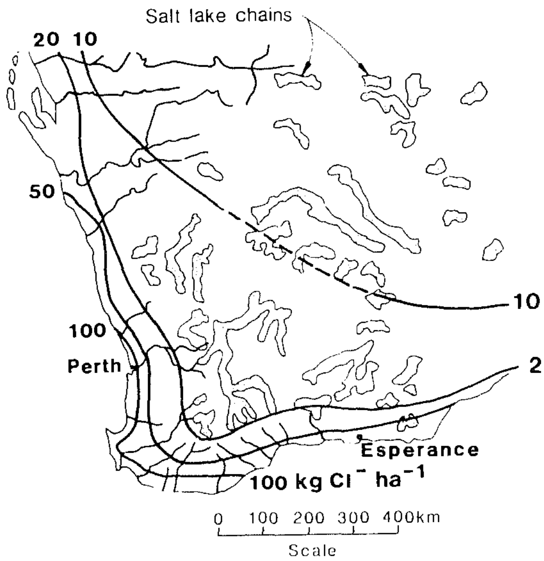

Figure 1. Chloride precipitated over south-west Western Australia during 1973 (kg Cl⁻/ ha) (adapted from Hingston and Gailitis, 1976)

Although some rainfall salt will be transported directly to streams, the main source of stream solutes is that leached from the soil which has accumulated over previous millennia. A strong correlation of increasing soil salt storage with decreasing rainfall (Figure 2) has been established for the south-west (Johnston *et al.*, 1980; Stokes *et al.*, 1980; Tsykin and Slessar, 1985). In high rainfall areas (>1100 mm/yr) groundwaters

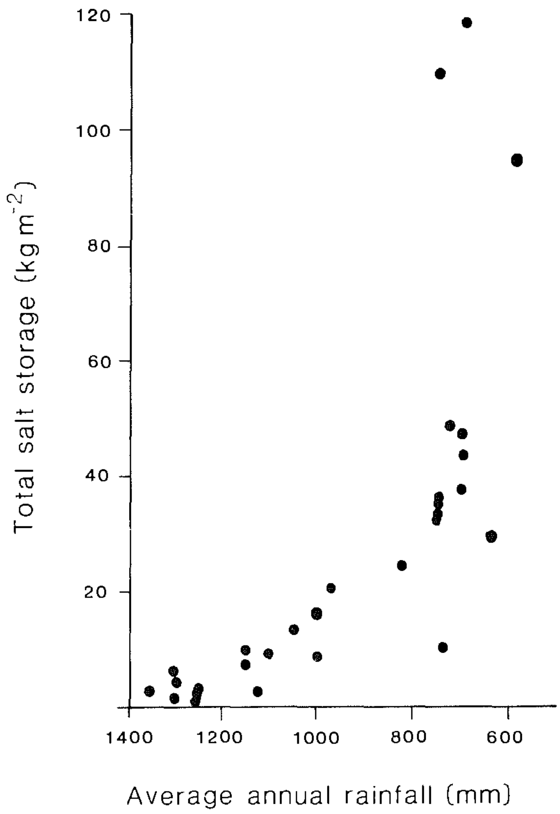

Figure 2. Variation of soil salt storage with average annual rainfall (after Stokes *et al.*, 1980)

discharge solutes freely to streams and salt is not retained significantly in the soil. As rainfall decreases, groundwater discharge in forest areas becomes intermittent to non-existent, leading to salt retention in the soil profile.

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 and increase or initiate groundwater discharge to streams. Salt stored in the soil profile is mobilised and leached to streams, resulting in increased stream salinity.

4. *Regional Impact of Agricultural Development on Stream Salinity*

The impact of agricultural development on stream salinity depends strongly on annual rainfall, as shown in Figure 3. In high rainfall areas soil salt storage is low and streams are fresh. In low rainfall areas soil salt storage is high. When groundwaters discharge salt to streams following clearing, stream salinities become high in these areas.

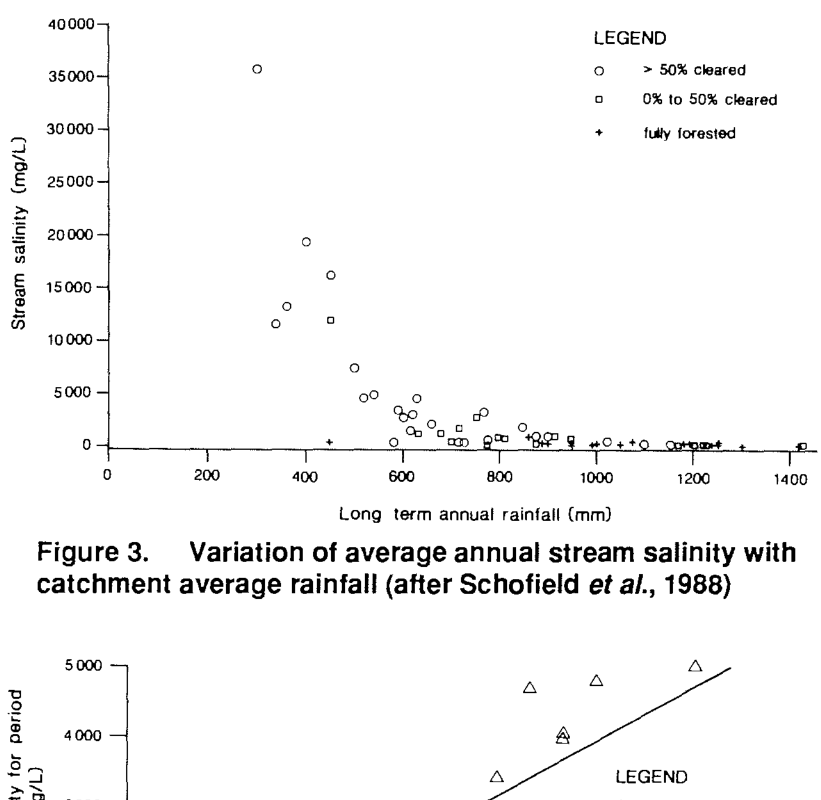

Figure 3. Variation of average annual stream salinity with catchment average rainfall (after Schofield *et al.*, 1988)

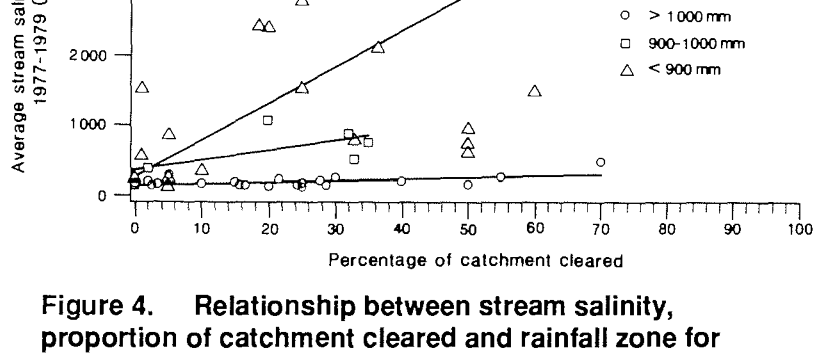

Figure 4. Relationship between stream salinity, proportion of catchment cleared and rainfall zone for subcatchments of the Shannon, Warren and Donnelly Rivers (adapted from Collins and Barrett, 1980)

The magnitude of the stream salinity increase is also affected by the proportion and location of agricultural clearing. There is a clear trend for stream salinity to increase with area cleared (Figure 4). The rate of increase in salinity with area cleared is greater the lower the average rainfall.

A regional distribution of the surface water resources, their salinities and rates of salinity change for south-west Western Australia is shown in Figure 5. Streams have been categorised as fresh, marginal, brackish and saline (see Appendix I for definitions). It is clear from Figure 5 that the major rivers of the region are already badly salinised and their salinities are increasing. 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 (Western Australian Water Resources Council, 1986)

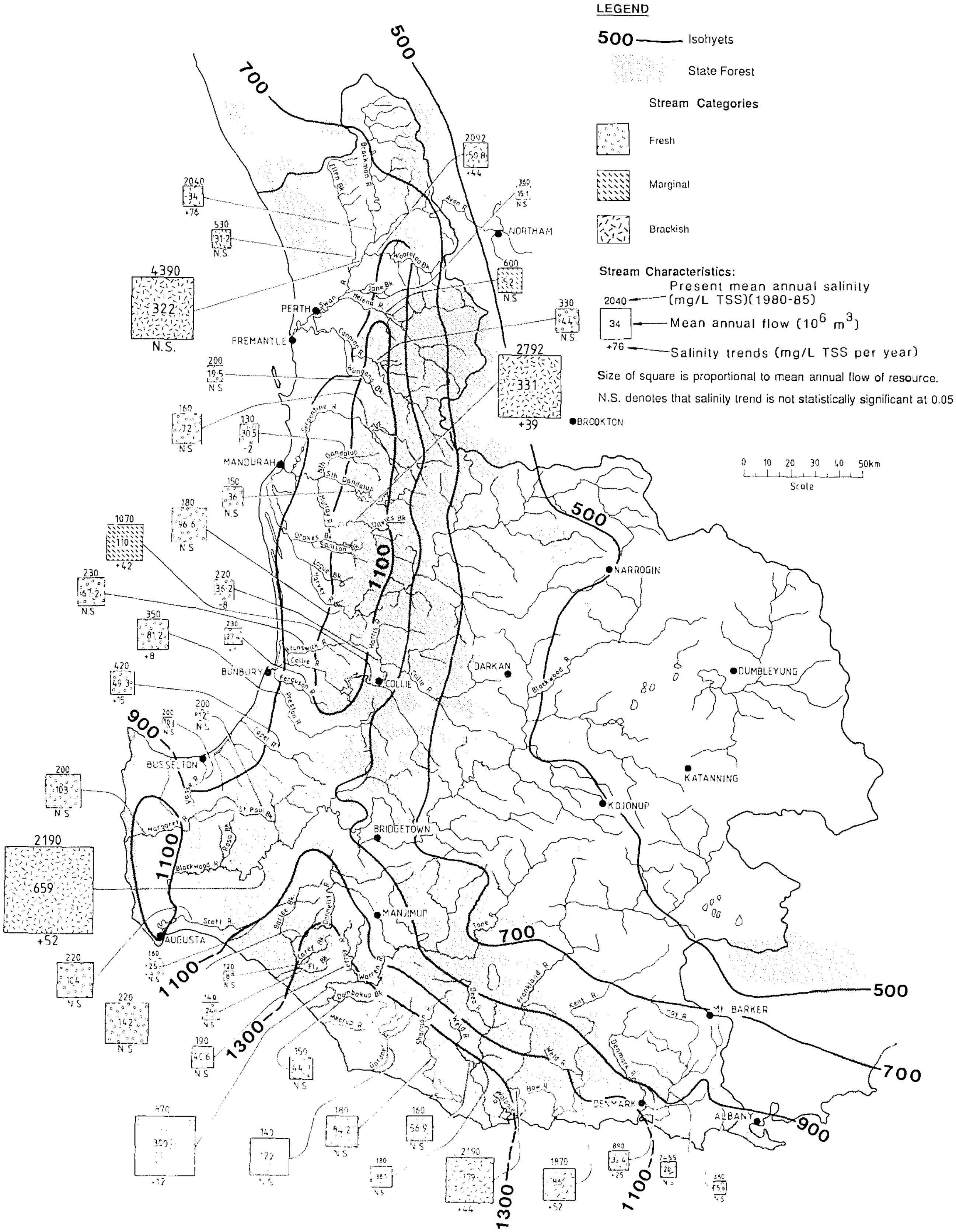

Figure 5. The distribution of surface water resources, salinities and rates of salinity change in relation to rainfall and forest cover (after Schofield, 1989)

5. *Trends in Stream Salinity*

Monitoring of flow and salinity data over the last 20 to 40 years in south-west Western Australia has enabled a regional analysis of stream salinity trends. Stream salinities in fully forested catchments have been declining over the last two decades. Examples of this in high, intermediate and low rainfall catchments are shown in Figure 6. The decline in stream salinity 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 (Figure 5). 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. Four potential domestic water supply streams with partially cleared catchments below 1100 mm/yr rainfall have salinities which are continuing to deteriorate. These are the Collie, Denmark, Warren and Kent rivers (Figure 7). Many of the major rivers which have been extensively cleared have shown very high rates of stream salinity increase over the last 20 years.

The salt export from catchments with agricultural clearing is substantially in excess of the salt input in rainfall. Thus salt is being leached from the soil store which will deplete over time. Peck and Hurle (1973) calculated the characteristic leaching times to range from 30 years in the high rainfall zone to 400 years in low rainfall areas. Stream salinity will thus increase, level off and decrease, passing through these phases more quickly in high rainfall areas than low rainfall areas. In the case of the Collie River (Wellington Dam), groundwater simulations predict that stream salinities would level off in about 50 years in the absence of reforestation (Hookey, 1987). As the clearing patterns on the other catchments in Figure 7 are similar to that of the Collie catchment, their increasing salinity trends can be expected to continue well into the next century.

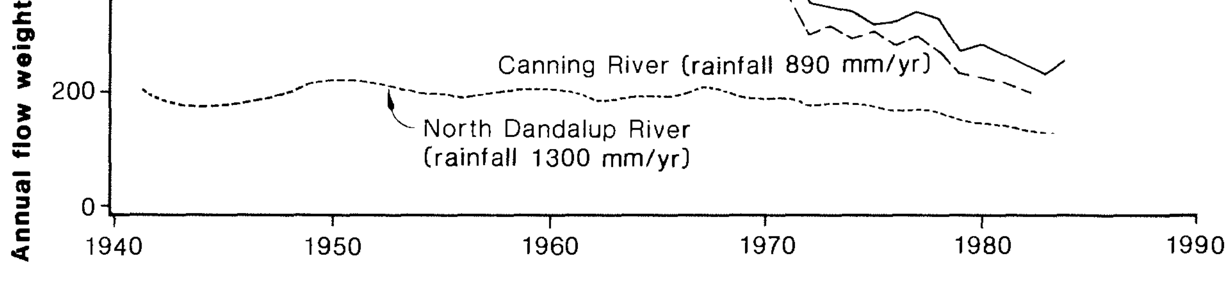

Figure 6. Stream salinity trends of forested catchments in high, intermediate and low rainfall zones (after Schofield *et al.*, 1988)

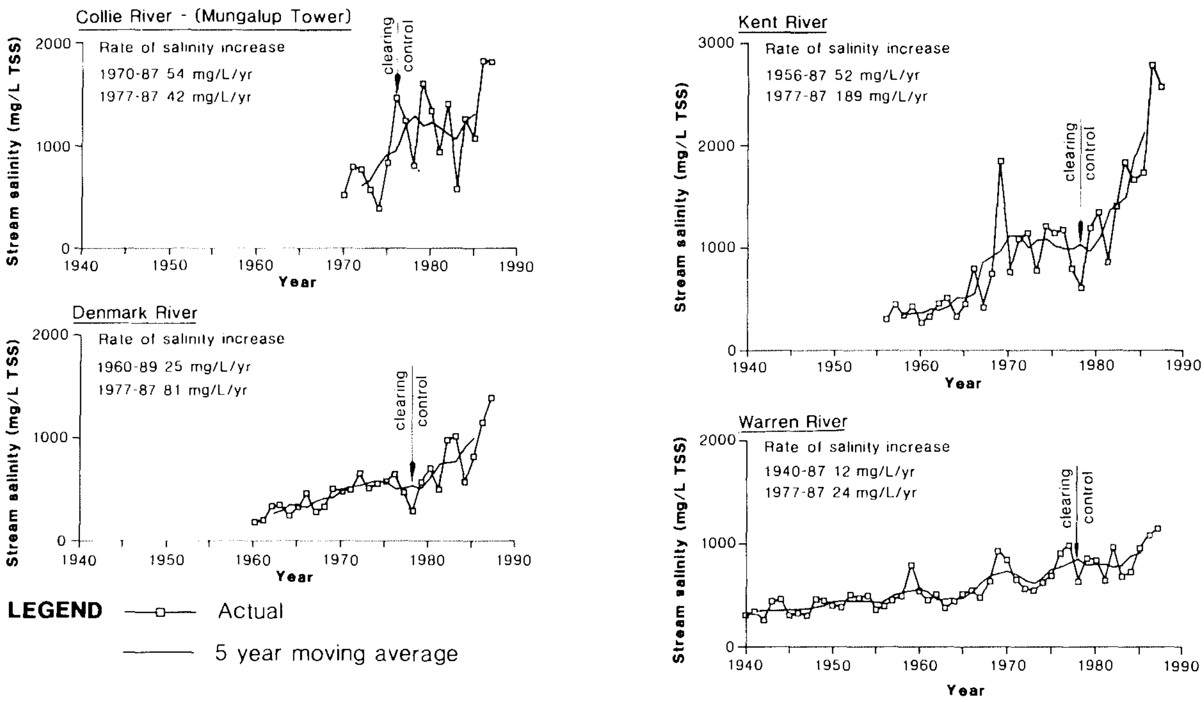

Figure 7. Stream salinity trends of potential future potable water supply catchments

6. *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 soil salt storage and extent of agricultural clearing. The principal high salt storage groups are forested, marginally cleared, extensively cleared and totally cleared. This classification has formed the basis of salinity management strategies.

The forested catchments with significant salt storage 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 bauxite mining and forest operations such as clearfelling, selection logging and thinning. 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 (Steering Committee for Research on Land Use and Water Supply 1984, 1987). 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 have stream salinities within or close to the marginal category and often have an increasing salinity trend. The catchments are predominantly forested, but extend inland to high salt storage areas which have been partially cleared for agriculture. The legislative actions to control land alienation and clearing since the 1960s have limited the expansion of agriculture in these sensitive catchments. At the time these controls were controversial and politically difficult to implement. They were the first in Australia to limit large-scale agricultural clearing in the post-war boom. Although they have been very cost-effective as a preventative measure, clearing prior to their implementation is still causing salinity problems. Stream salinities have continued to increase at an alarming rate on the Collie (42 mg/L/yr), Denmark (81 mg/L/yr), Warren (24 mg/L/yr) and Kent (189 mg/L/yr) rivers where clearing

Valley seep in east Collie catchment. Progression from scalded valley floor to salt-tolerant grasses upslope is evident.

A combination of increasing salinity and more water is resulting in the death of many trees at Lake *Wannamel.* It is the presence of live trees which makes *L. Wannamel* one of Western Australia's most important wetlands for the breeding of water birds.

Successful tree establishment in salt/waterlogging affected valley floors is essential for stream salinity reclamation. Seen here is the successful establishment of river red gum (*E. camaldulensis* -right) and swamp sheoak (*Casuarina obesa* -left) in a mounding and drainage trial.

Agroforestry in the form of wide-spaced plantations has been shown to improve land productivity and also has the capacity to lower saline groundwater tables.

Valley plantings in the east Collie catchment. This strategy is being used operationally in the Wellington catchment reforestation programme to control stream salinity.

Tasmanian blue gum (*E. globulus*) 9 month old coppice (foreground) and at age 8 years (background). This species has high commercial potential for pulpwood production on farmland.

Ventilated chamber measures barley transpiration at Bowelling. Barley is one of a number of crops which has higher water use than traditional pasture.

Tagasaste (*Chamaecytisus proliferus*) harvesting at Dandaragan. Well managed Tagasaste has superior productivity and water use than traditional pasture on deep sands.

controls have been implemented. Futher supplementary action is required to reverse the stream salinity increases if these water resources are to be viable as future water supplies. Partial catchment reforestation has been the most promising approach of a range of possible options. This was initiated on the Collie catchment in 1979/80.

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 category (Figure 5) 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.

The surface water catchments suitable for partial reforestation have similar hydrological features. In their high rainfall parts they are characterised by high volume, low salinity yields, whereas the opposite holds in their low rainfall areas. Typically 80% of the total salt load but less than 30% of the total streamflow volume is generated from the agriculturally developed land below the 900 mm isohyet. An important feature of these catchments is that significantly increased water yields from the high rainfall forested areas (as a result, for example, of forest thinning or clearing) would not be sufficient to maintain their salinities within potable levels (Loh and Stokes, 1981). The control of salinity can only be achieved by reducing salt discharge from the cleared land below the 900 mm isohyet.

7. *Reforestation Strategies*

Research to develop appropriate strategies for partial reforestation has involved tree selection and establishment and an evaluation of a range of tree planting strategies with respect to groundwater and stream salinity control.

7.1 Tree Selection

The initial criterion for tree selection is adaptation to the environment. In south-west Western Australia this includes adaptation to climate, soils, pests, diseases, fire, and in some locations waterlogging and salinity. Adaptation to a given site may vary with genus, species or provenance.

Only a few species have so far been identified which have provenances adapted to waterlogging and salinity (saline seep) conditions. These include *Casuarina obesa, Eucalyptus sargentii* , *E. camaldulensis* and *E. occidentalis.* These species can provide some secondary benefits in addition to salinity control but not sufficient to make them commercial propositions based on returns from their secondary benefits only.

Further progress in tree selection for salt/waterlogging conditions is expected from research into the identification, cloning and testing of potentially high salt/waterlogging tolerant trees (Bell and van der Moezel, 1989) . Over the past four years, 100 species, 323 provenances and 16736 seedlings have been screened for salt/waterlogging tolerance. Of these 410 seedlings were selected for micropropagation research. Successfully micropropagated individuals are now available in *Eucalyptus, Melaleuca* and *Casuarina,* and clones of the first of these are being produced for field trials.

For well drained soils, away from saline seeps, a wide range of adapted species have been identified. Several are considered to have commercial potential. These include *Pinus radiata* for timber and other wood products and the fast growing eucalypts *E. globulus, E. viminalis, E. botryoides* and *E. saligna* for pulpwood production.

Having satisfied the adaptation criterion, the other two main criteria are water use and commercial value.

Knowledge of the water use capacity of various species for a range of conditions could allow trees to be selected to maximise the effectiveness of reforestation or minimise the area of agricultural land required for reforestation. Comparative water use, however, has been difficult to quantify accurately in the field.

The commercial value of species has been easier to determine and there are good data on some *Eucalyptus* and *Pinus* species.

An economic analysis of *P. radiata* forestry in the Manjimup region (Malajczuk *et al.*, 1984) found that it could be very competitive with grazing.

Table 1: Characteristics of experimental reforestation sites

Site	Planting year	Main species planted	Proportion of site cleared (%)	Proportion of cleared area replanted (%)	Initial planting density (stems-/ha)	Estimated stem density in 1986 (stems-/ha)	Mean reforestation crown cover at Dec 1987 (%)	Initial* depth to water table (m)	Initial ground-water salinity (mg/L)	Depth of weathering (m)
Flynn's Farm										
Landscape	1977	*E. wandoo* *E. camaldulensis* *P. pinaster* *P. radiata*	98	8	670	500	43	2.1	4600	0-20
Hillslope	1978/ 1979	*E. camaldulensis* *E. wandoo*	100	54	1 200	1 000	29	3.3	7400	5-20
Agroforestry	1978	*P. radiata* *P. pinaster* *E. camaldulensis*	51	58	380/ 760/ 1 140	75/ 150/ 225	14	4.4	2400	3-13
Stene's Farm										
Strip Plantings	1976 to 1978	*E. camaldulensis* *P. radiata* *E. globulus* *P. pinaster* *E. wandoo*	31	14	1 200	600	47	2.7	7700	>20
Valley Plantings	1979	*E. wandoo* *E. rudis* *E. camaldulensis*	44	35	625	500	41	6.3	5400	>20
Agroforestry	1978	*E. camaldulensis* *E. sargentii* *E. wandoo*	25	57	1250	150/ 900	25	2.7	6600	>20
Arboretum	1979	63 *eucalypt* plus 2 pine species	35	70	625	0–600	39	7.1	5400	>20

** depth corresponds to the lowest groundwater level during the year.*

The main disadvantage is the long wait for returns from the timber crop. The State Government has developed sharefarming schemes whereby a farmer can receive an annuity plus a share of the revenue at harvesting from the State, thus overcoming the delay in forestry returns.

A number of eucalypt species also show promise for growing in dense plantations to produce pulpwood. Good quality farmland could give timber yields ranging from 15 cubic metres per hectare per year (m^3/ha/yr) at 600 mm/yr rainfall to more than 25 m^3/ha/yr at 900 mm/yr rainfall, providing annuities under a sharefarming system of $80–140/ha/yr. The outlook for a short rotation (7–10 years) eucalypt sharefarming industry with dense plantations for pulpwood is sufficiently attractive to warrant large scale commercial development. The State Government has recently announced that a 'Tree Trust' will be established to co-ordinate a pulpwood cropping industry.

7.2 Tree Establishment

Site preparation includes ripping and herbicide spraying for pasture (weed) control prior to planting in June or July. Seedlings are fertilised once. In saline seep areas seedlings are planted into ridge mounds. Recent research (Ritson and Pettit, 1988) indicates that a double ridge mound with

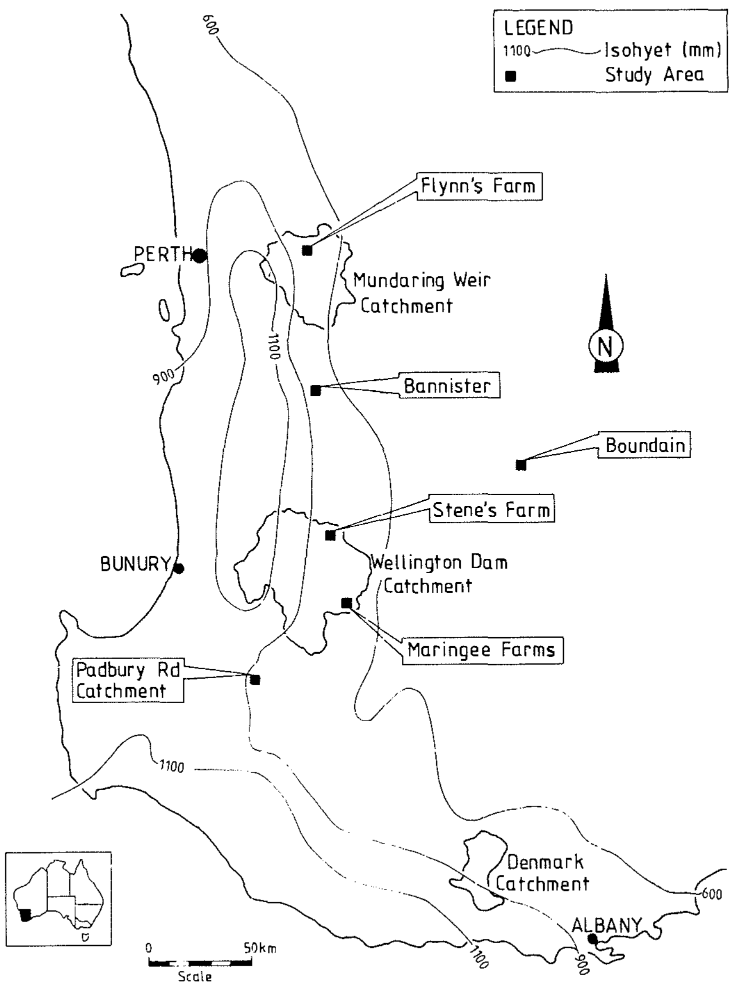

Figure 8 Location of reforestation study areas

seedlings planted in the trough between the ridges gives better establishment success than a single ridge mound.

7.3 Evaluation of Reforestation Strategies

A number of experimental reforestation sites were established in the late 1970s (Figure 8). The characteristics of these sites are summarised in Table 1. The sites have been evaluated in terms of their effectiveness in controlling salinity (Bell *et al.*, 1988; Schofield *et al.*, 1989). Timber, pulpwood and pasture production (in agroforestry layouts) were also evaluated but are not discussed further here.

7.3.1 Effect of reforestation strategy on groundwater level

Four partial reforestation strategies were tested : (A) lower slope and discharge zone planting; (B) wide-spaced plantations covering most of the cleared area; (C) strips or small blocks strategically placed but covering a small proportion of the cleared area; (D) dense plantations covering a high proportion (>50%) of the cleared area. In each strategy a component of lower slope and/or discharge zone planting was included. This was considered necessary if groundwater solute discharge to streams was to be eliminated.

(A) Lower slope and discharge zone planting strategy

Reforestation trials have been conducted at two sites using this strategy. Only one site however has data for interpretation. At this site, Stene's Valley Plantings (Figure 9), 35% of the cleared area was replanted with *E. wandoo*, *E. rudis* and *E. camaldulensis* in 1979. The initial annual minimum depth to groundwater beneath the plantation was 6.3 metres and the initial groundwater salinity was 5 400 mg/L TSS. Over the period 1979–88 there has been a lowering of the groundwater table beneath the reforestation of 2.0 metres, whilst under pasture the groundwater level rose by 0.4 metres (Figure 10). The groundwater table responses beneath pasture, reforestation and native forest are shown by comparing annual minimum valley cross-section potentiometric surfaces of 1979 and 1988 (Figure 11). Over this period the groundwater levels have lowered beneath the reforestation but have risen slightly beneath the midslope pasture.

(B) Wide-spaced plantations

Reforestation in which trees are thinned to or planted at a wide spacing (low density), with pasture grazing between trees, has been investigated at Flynn's Agroforestry, Stene's Agroforestry and Boundain.

At Flynn's Agroforestry (Figure 12), *Pinus radiata*, *P. pinaster* and *E. camaldulensis* were planted in 1978 and thinned between 1982 and 1985. The reforested area covered 58% of the cleared area. The initial depth to groundwater was 4.4 metres and the average groundwater salinity was 2400 mg/L TSS. Over the period 1979–88 the groundwater levels beneath the reforestation

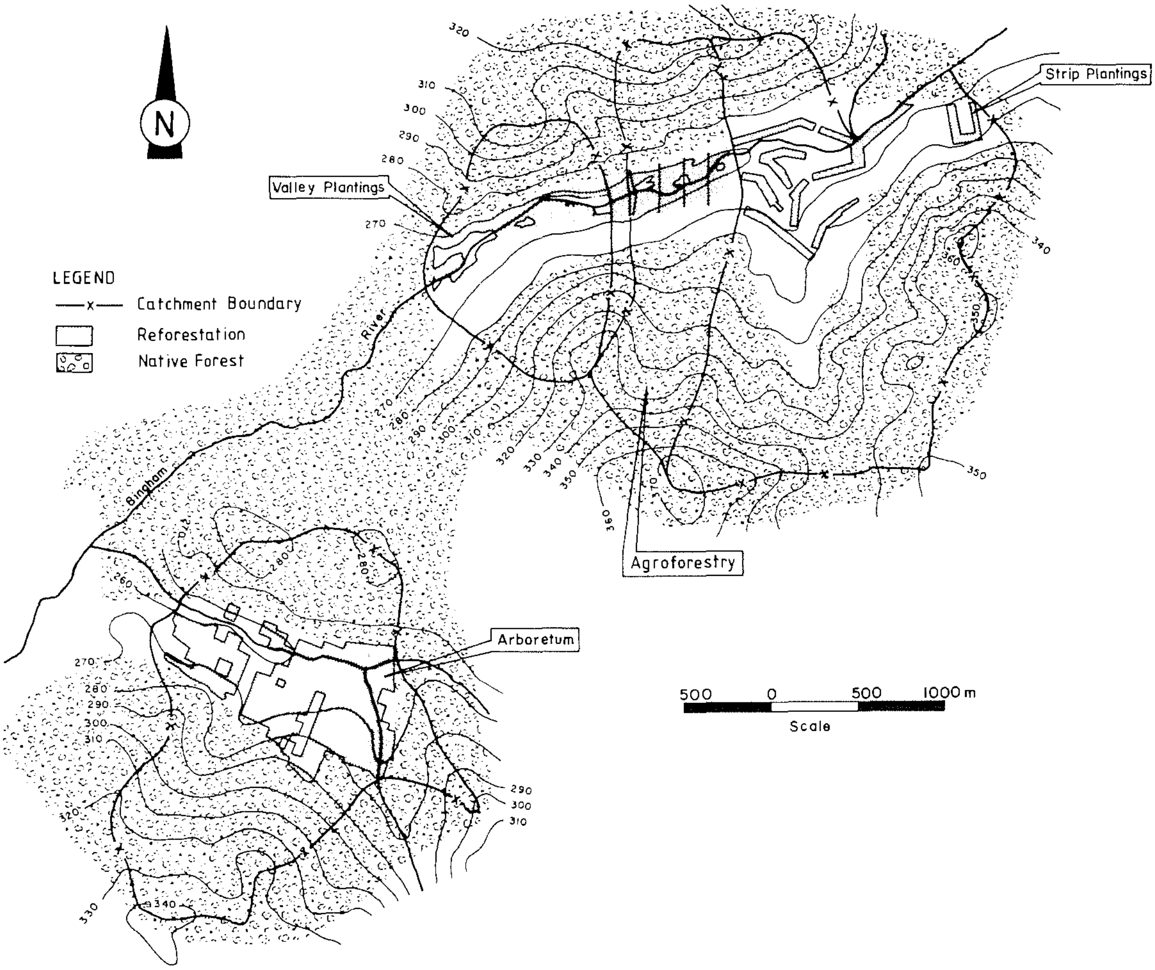

Figure 9. Stene's Farm experimental reforestation sites

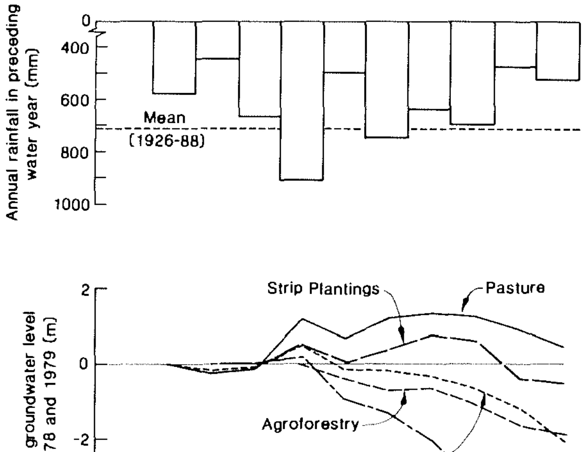

Figure 10. Annual rainfall and groundwater level variations at Stene's Farm experimental reforestation sites

declined by 1.2 metres while over the same period groundwater under pasture at a nearby site decreased by 0.5 m (Figure 13).

At Stene's Agroforestry (Figure 9), *E. camaldulensis*, *E. sargentii* and *E. wandoo* were planted at a uniform density in 1978 and were thinned to differing densities in 1981. The reforested area covered 57% of the cleared area. The initial depth to groundwater was 2.7 metres and the groundwater salinity was 6600 mg/L TSS. The groundwater level over the period 1982–88 averaged over the whole reforested area has shown a net decline of 1.8 metres while under pasture at an adjacent site the groundwater level rose by 0.4 metres (Figure 10).

At Boundain (500 mm/yr average rainfall) an agroforestry trial was established in 1981 adjacent to an expanding salt seep. Groundwater occurred at a depth of 1.3 metres and had a salinity of 2000–17 000 mg/L TSS. Trees were planted at 166 stems/ha and 83 stems/ha in 40 x 150 metre plots, with every third plot left with annual

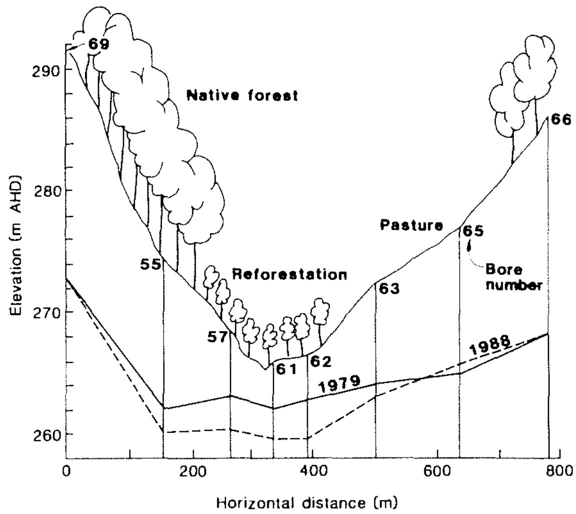

Figure 11. Comparison of annual minimum valley cross-section groundwater levels of 1979 and 1988 at Stene's Valley Plantings

pasture. This layout was replicated five times. Tree species were planted according to salinity hazard. *E. globulus* was planted on non-saline areas, *E. camaldulensis* adjacent to the seep and *E. occidentalis, E. sargentii* and *Casuarina glauca* (salt sheoak) on salt-affected land. Over the period 1981–1988 the average groundwater level was depressed beneath reforestation by 1.0 metre while groundwater beneath pasture was only depressed 0.25 metres (Figure 14a). The magnitude of the groundwater depression was significantly greater beneath the higher density plantings (166 stems/ha) than the lower density plantings (83 stems/ha) (Figure 14b).

(C) Strip and block planting

This strategy involves strategically planting strips or blocks of trees on cleared land, allowing agriculture to be continued on the unplanted areas. Three reforestation trials of this type have been conducted: Flynn's Landscape, Stene's Strip and Bannister.

At Flynn's Landscape site (Figure 12), blocks of trees were planted on the lower slopes in 1977 covering 8% of the cleared area. Blocks were 50 or 100 metres wide and included *E. wandoo, E. camaldulensis, P. pinaster* and *P. radiata*. The initial groundwater depth and salinity beneath the plantations were 2.1 metres and 4600 mg/L TSS respectively. Over the period 1979-88 there was a depression of groundwater level beneath reforestation of 0.9 metres, while beneath pasture there was a reduction of 0.5 m (Figure 13).

On the Stene's Strip site (Figure 9), widely distributed strips covering 14% of the cleared land were planted from 1976 to 1978. The strips were 30–40 metres wide and their configuration ensured a minimum spacing of 200 metres. The main species planted were *E. globulus, E. camaldulensis, P. radiata, P. pinaster* and *E. wandoo*. The initial average depth and salinity of groundwater beneath the plantations were 2.7 metres and 7700 mg/L TSS respectively. Over the period 1979–88, the groundwater levels under the strips lowered on average by 0.5 metres, whilst under pasture the groundwater level rose by 0.4 metres (Figure 10).

The Bannister site (Figure 8) was established in 1975 and comprised two block plantings, one upslope and one midslope just above a salt seep. The total area planted covered 14% of the cleared land and included 25 different species. The initial depth to groundwater beneath the plantations ranged from 2–8 metres and the groundwater salinity (in 1985) ranged from 1000–9600 mg/L TSS. Over the period 1977–87 there was no significant lowering of the groundwater table under the plantations and no significant difference to groundwater level under pasture. Measurement of soil water profiles at this site indicated that trees were extracting unsaturated

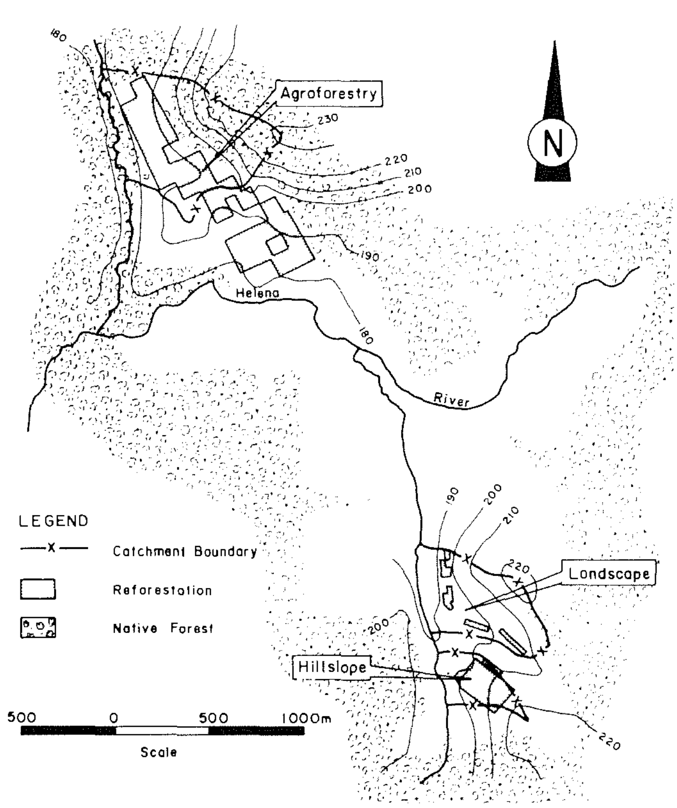

Figure 12. Flynn's Farm experimental reforestation sites

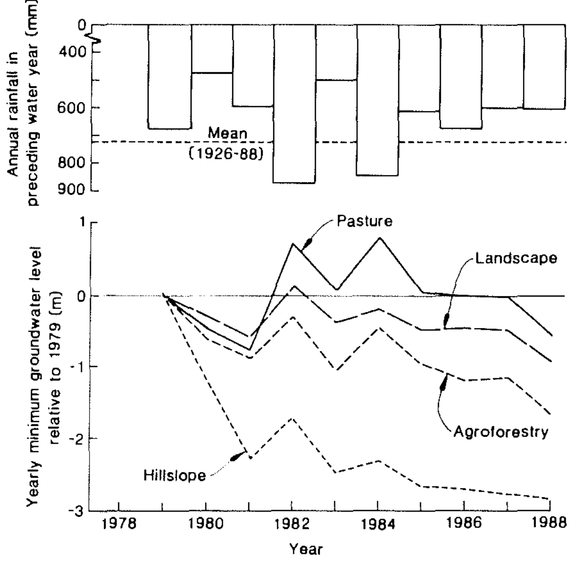

Figure 13. Annual rainfall and groundwater level variations at Flynn's Farm experimental reforestation sites

soil water over summer up to depths of 10 metres, while water extraction by pasture was limited to a depth of 0.5 metres.

The poor performance of the block and strip plantings is attributed to the low proportions of cleared area replanted.

(D) Dense, extensive plantations

Dense plantations covering a large proportion of the cleared areas have been studied at three sites, Flynn's Hillslope, Stene's Arboretum and Padbury Road catchment (Figure 8).

Flynn's Hillslope (Figure 12) was planted with *E. camaldulensis and E. wandoo* at a density of 1250 stems/ha in 1978 and 1979. The plantation covered 54% of the hillslope which was totally cleared prior to reforestation. The initial depth and salinity of groundwater beneath the plantation were 3.3 metres and 7400 mg/L TSS respectively. The groundwater table was lowered 2.8 metres over the period 1979–88 while the groundwater level beneath pasture decreased by 0.5 m over the same period (Figure 13).

At Stene's Arboretum (Figure 9) 65 species were planted in 1979 on 0.5 hectare plots covering 70% of the cleared area. The initial depth to groundwater ranged from 1.2 to 19.4 metres and the average initial groundwater salinity was 5400 mg/L TSS. Over the period 1979–1988 there was a net lowering of groundwater level under reforestation by 5.6 metres, while under

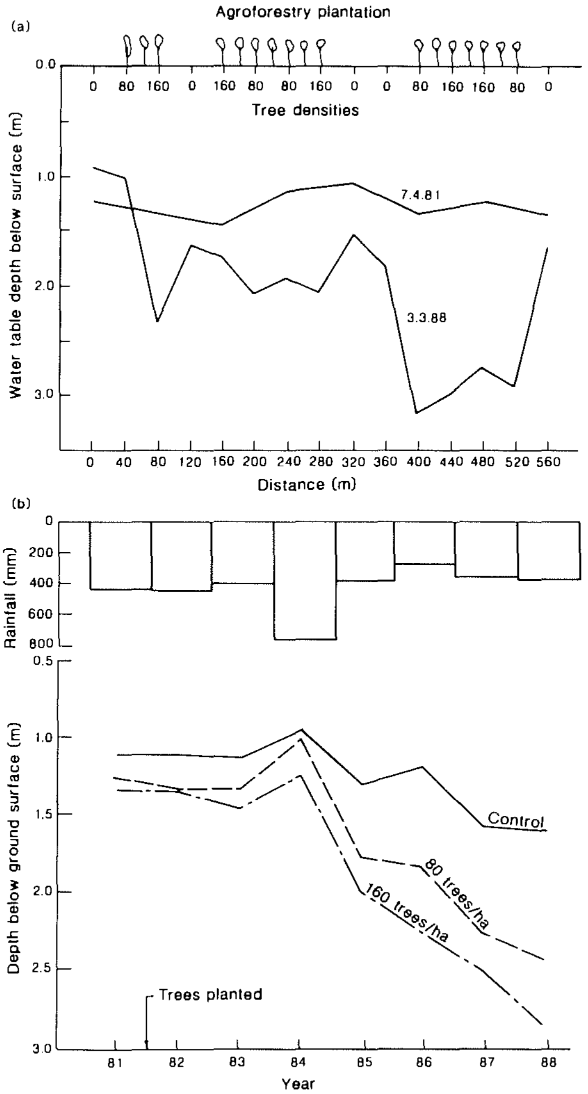

Figure 14. Groundwater and rainfall variations at Boundain: (a) comparison of groundwater levels across the site between 1981 and 1988, (b) annual rainfall and groundwater level variations beneath pasture and agroforestry plantations

pasture at a nearby site groundwater levels increased by 0.4 metres (Figure 10).

7.3.2 Effect of reforestation area and density on groundwater level

The effectiveness of the various reforestation strategies in reducing groundwater level beneath plantations of age 10 years has been found to depend primarily on the area and density of trees planted. A regression of average rate of water table reduction against proportion of cleared area reforested is shown in Figure 15a. The four sites included in the regression have similar crown covers (39–47%) whereas the two sites excluded

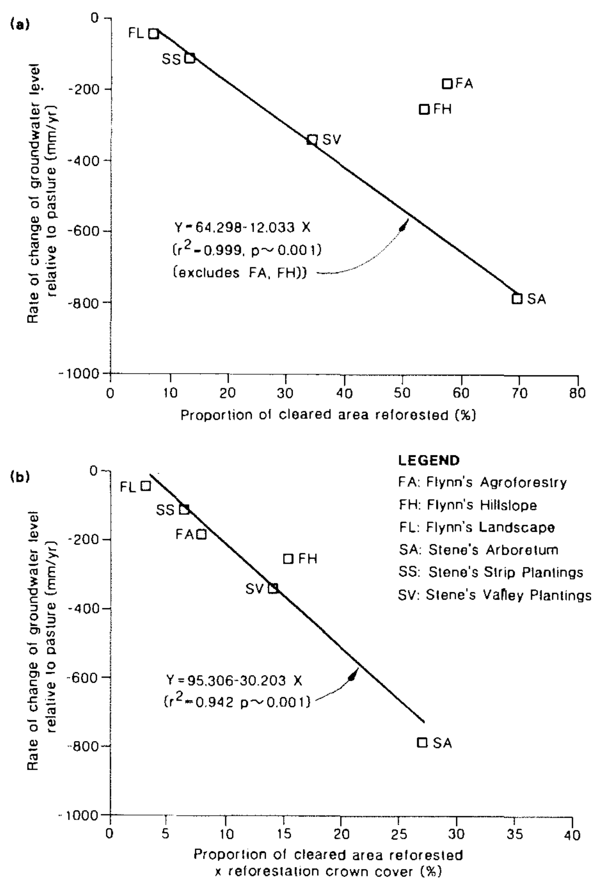

Figure 15. Dependence of mean rate of change of minimum groundwater level under reforestation relative to pasture on (a) proportion of cleared landscape reforested and (b) product of the proportion of the cleared landscape replanted and mean crown cover of reforestation

have significantly less crown cover (Flynn's Hillslope 29%, Flynn's Agroforestry 14%). Over the measurement period the groundwater levels beneath pasture at Flynn's and Stene's sites lowered on average by 6 mm/yr. Using this information and the regression in Figure 15a, it can be shown that reforestation of 21.5% of the cleared area is required to lower the water table at a rate of 200 mm/yr (i.e. 2 metres over 10 years) relative to the ground surface.

Rainfall over the measurement period was 10% less than the long term (1926–88) average. If rainfall had been the long term average it is estimated that groundwater levels beneath pasture on Flynn's and Stene's sites would, on average, have risen at a rate of 360 mm/yr (Bell *et al.*, in press). In this case the regression of Figure 15a indicates that about 52% of the cleared area would need to be reforested to lower the water table at 200 mm/yr relative to the ground surface.

A second regression which takes into account the crown cover of the reforestation is shown in Figure 15b. In this example the average rate of water table reduction was regressed against the 'total percentage tree cover' as represented by the product of proportion of cleared land reforested and reforestation crown cover. The quality of this regression, which includes all sites, implies that total percentage tree cover is the most important factor (for the given reforestation strategies) in the lowering of the water table beneath reforested areas.

7.3.3 Effect of reforestation on groundwater and soil salinity

In the past concern has been expressed about the potential of salt concentration to increase beneath reforestation stands located in valley floor and lower slope locations and affect their long term viability (Conacher, 1982; Morris and Thomson, 1983; Williamson, 1986). Borehole monitoring at all sites above 700 mm/yr rainfall showed salinity at the water table to have decreased (Schofield *et al.*, 1989). At one site, with rainfall of about 500 mm/yr, groundwater salinities have increased. There is also evidence trees are particularly susceptible to combined salt-waterlogging stress in south-west Western Australia (van der Moezel *et al.*, 1988) in which case lowering the water table would improve the viability of the stands due to reductions in waterlogging.

Measurement of soil salt content at Boundain showed that, under reforested areas, salt content decreased over the depth range 0 to 0.75 metres, increased over the depth range 0.75 to 2.25 metres and remained the same below 2.25 metres. Under pasture there was little change in the salt content profile.

7.3.4 Effect of reforestation on salt export

The Padbury Road catchment (880 mm average annual rainfall) was planted with *P. radiata* and *E. globulus* over the period 1977–83. Measurements were taken of stream yield, stream salt discharge and stream salinity and were analysed by Bell *et al.* (1987). By 1986 it was found that the stream yield and salt discharge of the catchment had decreased in the same proportion, to about 10% of what it would have been without reforestation. Since yield and salt discharge decreased in the same proportion, stream salinity remained almost unchanged. The lack of a decrease in stream salinity may be partly attributed to leaving the small valley floor (approximately 4% of the catchment) under pasture, which has allowed some continued saline groundwater discharge. The results suggest that intensive reforestation of the type carried out would not improve the water quality of small, local water supplies in the first 10 years and would in fact strongly decrease the water yield. The result is very significant, however, for salinity control in large water supply catchments, because reforestation of the major salt-exporting lower rainfall areas would significantly reduce the stream salinity at the catchment outlet. Establishing plantations in the higher rainfall areas of these catchments should be avoided since this would reduce the contribution of fresh water to the stream and increase the stream salinity.

8. Agricultural Strategies

8.1 Pasture and Crop Manipulation

Research in Western Australia into agronomic options for controlling salinity has concentrated on measuring evapotranspiration of different pasture and crop species as an indicator of their importance in controlling groundwater recharge and hence salinity. All studies have shown that the widely used subterranean clover-based annual pasture has low water use relative to crops and perennial pastures (Oram and Cooke, 1982; Nulsen, 1984). This could be partly explained by its shallower rooting depth.

Of the perennial pastures, lucerne has been shown to be high water using. Phalaris is also promising. Over 500 000 ha of present agricultural land is considered suitable for perennial pastures, principally in the southern agricultural areas (Biddiscombe *et al.*, 1982). More work is required, however, on their adaptation, productivity and persistence in areas receiving less than 900 mm annual rainfall and with marked seasonality.

Crops of lupins, oats, rape and barley have all been found to have higher water use than annual pastures. The water use of crops could be maximised by optimising times for planting and fertiliser application, selecting optimum varieties, and minimising waterlogging.

8.2 Surface Drainage

Waterlogging has been identified as a significant factor in reducing crop yields (and hence evapotranspiration) in the south-west agricultural areas (Negus, 1983). Waterlogging may also lead to increased groundwater recharge.

Shallow drainage systems have been shown to discharge significant amounts (2–18% of rainfall) of surface and shallow perched water (Cox, 1988). Waterlogging was reduced at distances of up to 80 metres downslope of a drain. Well designed shallow drains on non-saline land could also reduce stream salinity by decreasing groundwater recharge and adding fresh water to streams. Interceptor drains which do not effectively discharge water and soil conservation structures which purposely retain water could increase groundwater recharge and hence increase stream salinity. By itself surface drainage would not be a sufficient strategy to control stream salinity (PWD, 1981). However, where extensive upland waterlogged areas exist, surface drainage, when integrated with other measures, has some potential to ameliorate stream salinity.

8.3 Fodder Crop Trees

Fodder crop trees have the potential to be higher water users than traditional crops and pastures. In Western Australia there has been no comprehensive species selection programme.

Tagasaste (*Chamaecytisus proliferus*) is well adapted to many soils and, based on two studies, has promising water use and in certain conditions the ability to lower the groundwater table relative to annual pasture. Its economic value appears to be considerably greater than annual pastures when grown on deep sands but not significantly better for soils which normally produce good annual pastures. Further research is required on this species, and a number of other fodder trees and shrubs that are well adapted to local conditions.

8.4 Saltland Agronomy

A considerable amount of research has been conducted on revegetating saline seeps in low rainfall (less than 500 mm/yr) agricultural areas using halophytic (salt-tolerant) vegetation. The main aim has been to produce fodder from saline sites and reduce soil erosion.

From the limited research on water use by halophytic shrubs it appears that their evaporation rates are considerably better than bare soil. *Atriplex* species are well adapted to harsh saline sites (where trees are difficult to establish) and have been able to lower the water table slightly in low rainfall (less than 500 mm/yr) areas (Greenwood and Beresford, 1980).

9. Management Approach

It has become increasingly accepted in recent years that catchment management should involve all aspects of the physical and socio-economic environments which impinge on the catchment and its use. From this has evolved the concept of integrated catchment management which attempts to integrate all aspects of water and land management and the associated agencies and communities to solve specific environmental problems. The integrated catchment management approach has been adopted by the Western Australian government and is being evaluated on the Denmark River catchment. This initially will involve three years of surveying and detailed farm planning to meet the objective of reducing stream salinity while maximising land productivity.

Following extensive land capability and geophysical surveying it is intended to utilise reforestation with commercial and sub-commercial (salt-tolerant) trees, higher water using agricultural plants and surface drainage techniques to achieve specified goals.

On the Wellington Dam catchment the current reforestation programme is to continue to the early 1990s. Over the period 1979 to the end of 1988, 5700 hectares of farmland had been reforested (Figure 16). The operational reforestation strategy has been to reforest about 30% of the cleared land, locating plantations on the lower slopes. Reforestation of severely affected saline seeps in valley floors is awaiting the development of suitable establishment techniques. Trees planted to date have been largely non-commercial, salt tolerant species.

A major review is underway to develop a new catchment management strategy to restore the whole water resource to potable levels in the forseeable future. The fundamental features of the new strategy will be :

(i) reforestation of salt/waterlogging-affected valley floors with techniques currently being developed;

(ii) reforestation of lower to middle slopes with commercially attractive trees;

(iii) use of agronomic and other strategies to minimise groundwater recharge on remaining agricultural land;

(iv) implementation within the framework of integrated catchment management, emphasising both detailed farm planning and regional planning.

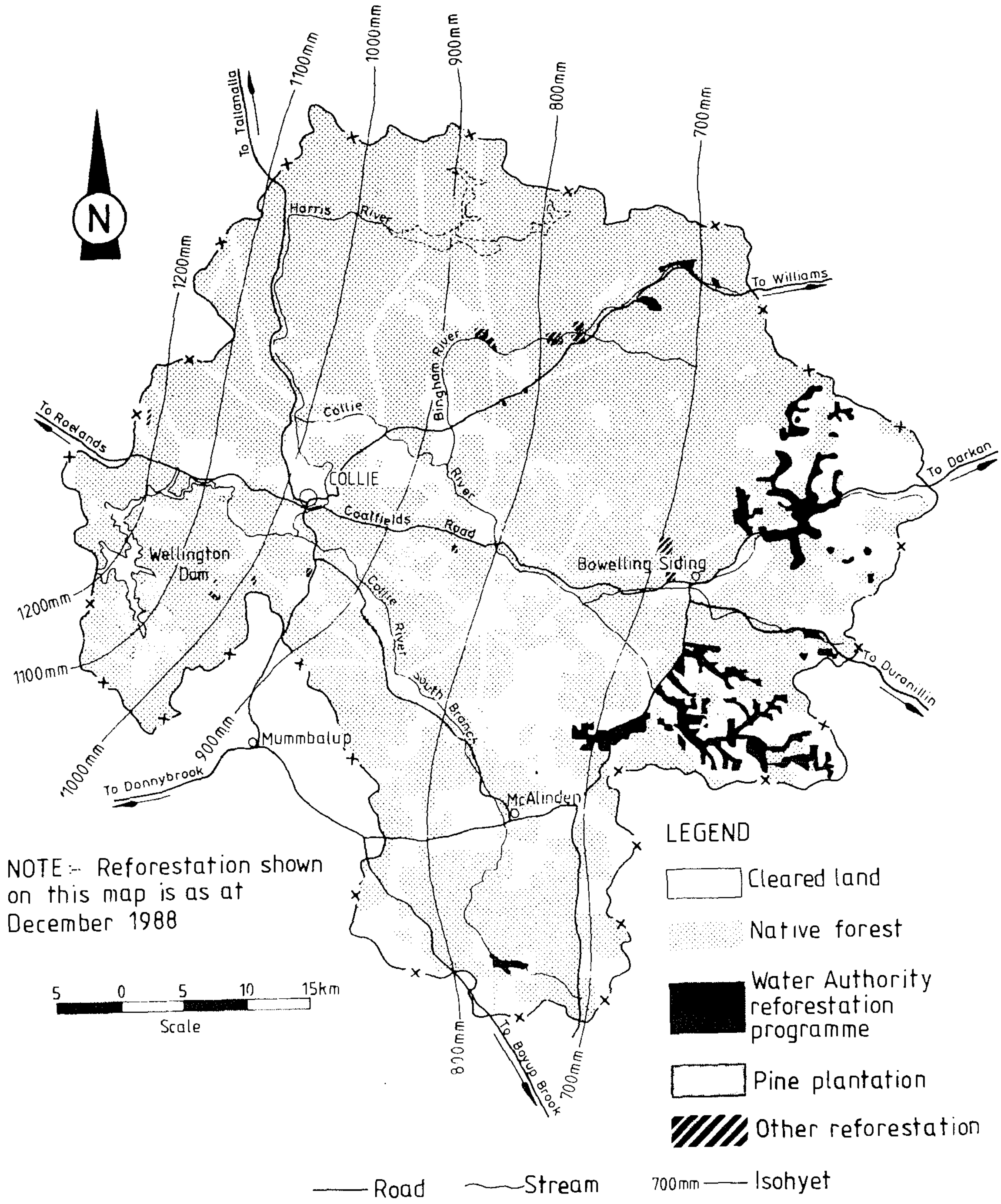

Figure 16. Wellington Dam catchment, showing areas of cleared land and reforestation (after Schofield *et al.*, 1989)

10. Implications for Management

• Identification of Salinity Management Priorities

There is a need 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.

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 for water supply purposes. Many of these catchments currently have rapidly increasing stream salinity. 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.

• Promotion of Integrated Catchment Management

The adoption of integrated catchment management systems by land managers is more likely to be successful if farmers, land owners, local communities and the general public are involved in their planning and development. Mechanisms to ensure that this occurs will need to be put in place.

• 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.

• Role of Remnant Native Vegetation in Salinity Control

Remnant vegetation on farmland needs to be included as a component in integrated catchment management. The policy and technical basis for such management needs to be rapidly developed. Elements of a management strategy should include encouragement to farmers to protect and manage remnants, especially where there is a priority for stream water quality protection and where such vegetation has been identified to have outstanding biological conservation value. Particular management techniques must be developed and made available to farmers. Where clearing is to proceed it should be conditional upon the implementation of treatments which will ensure the protection of soil and water values.

• Role of Commercial Tree Crops in Salinity Control

A commercially attractive tree cropping option for farmers would greatly enhance the potential for extensive treatment of salt affected catchments. The State's proposal to establish a Tree Trust to operate a pulpwood cropping industry is an initiative of considerable importance in the management of water resources in the south west.

However, a competitive tree cropping industry could attract interest in the higher rainfall areas (greater than 900 mm/yr rainfall) and significantly reduce fresh water yield thereby increasing the stream salinity of large catchments. Means of directing tree planting to lower rainfall areas where it would reduce salt discharge should be developed.

- ### Salinity as a Conservation Issue

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 (Northern Authur River Wetlands Committee, 1987).

11. Future Research Requirements

Ongoing Research

- Detailed hydrogeological studies of representative cleared catchments to better understand mechanisms of groundwater recharge and discharge should continue.
- Studies of the water and salt flows from catchments following clearing to determine the behaviour of stream salinity over time should be continued. 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.
- There is a continuing need to evaluate the range of approaches to integrate trees and farming, from wide-spaced stands to dense plantations, from strips of trees to remnant native forest. This involves measuring hydrologic response, measuring tree and agricultural production, developing management methods, and carrying out economic and social evaluations. In particular research which will increase the viability of pulpwood cropping as proposed by the Tree Trust is a high priority.
- Measurement of the responses of streamflow, salt discharge and stream salinity to reforestation of small and large catchments should be continued.
- Research to improve tree establishment in and adjacent to saline seeps should be continued. This should include both selection of more tolerant trees and development of better site amelioration techniques.
- A better understanding of salt dynamics beneath lower slope and valley floor reforestation to determine the potential for salt accumulation and to assess its effect on reforestation is required.
- Investigation of broad-scale survey methods to identify high recharge areas and potentially seep forming dolerite dykes is necessary.

Ongoing Research Requiring Upgrading

- Groundwater flow and solute modelling of catchments to predict the effects of different management options for lowering stream salinity and reducing land salinisation needs development.
- Models to predict future stream salinities of large water resource catchments under present and reforested conditions require enhancement. Such models will assist reforestation design and highlight management options and priorities.
- The hydrologic performance of species selected for growing in and adjacent to saline seeps needs evaluation.
- The potential for establishing perennial pastures as a salinity control measure requires evaluation.
- The effectiveness of wide-spaced plantations (agroforestry) in controlling groundwater levels and stream salinity requires further study.
- The fodder tree screening programme requires extension to water resource catchments and the salinity control potential of promising species evaluated.

Essential New Research

- The development of integrated catchment management systems and analysis of their hydrologic, economic and social implications is vital to future salinity control.

- Attention should be given 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.
- Research into the potential impacts of the Greenhouse Effect on agriculturally-induced stream salinity and its reclamation should be initiated.

Desirable New Research

- The wider amenity and habitat benefits likely to follow from extensive tree planting should be investigated.
- Alternative strategies (other than vegetation) for controlling stream salinisation should be investigated.

12. 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 degradation of wetlands and rivers of low rainfall areas has occurred.
- Stream salinities of a number of major rivers subjected to agricultural clearing are currently increasing at a rapid rate. Without further management, these stream salinities are predicted to increase for a further 20-50 years before declining over hundreds of years due to depletion of soil salt.
- 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 and reverse the continuing salinity deterioration on these catchments.
- Four catchments have high priority for the initiation or continuation of salinity management. These are the Collie, Helena, Denmark and Warren river catchments. The potential of a number of small water resources to develop salinity problems should be kept under review.
- A number of reforestation strategies have lowered groundwater tables relative to the ground surface during a period of below average rainfall.
- The rate of reduction of the groundwater table following reforestation is proportional to the area reforested and to the product of area reforested and crown cover.
- The area of dense reforestation required to lower the water table by two metres within ten years of planting, under recent below average rainfall conditions, has been about 22% of the cleared area. Under average rainfall conditions this figure is estimated to be 52%.
- To eliminate salt discharge to streams via groundwater it is necessary to have some lower slope and seep area reforestation in the vegetation strategy.

- Groundwater salinity beneath reforestation stands has decreased at most sites over the period 1979-86. Early concerns that lower slope plantations could be adversely affected by increasing groundwater salinity have not materialised to date.

- Tree species selection should be based firstly on adaptability to the site conditions. For adapted species, selection should proceed on the basis of commercial, conservation or environmental values and, when better data become available, water use characteristics.

- An extensive dense plantation has dramatically reduced salt discharge from one catchment in the 800-900 mm rainfall zone. This indicates that such reforestation would be highly effective in improving the stream salinity of large water supply catchments.

- Perennial pastures as well as crops have been shown to transpire significantly more water than annual clover-based pasture. Thus agronomic manipulation has the potential to ameliorate salinity problems.

- Other agricultural strategies, including shallow drains, fodder crop trees and halophytic shrubs have all shown potential for ameliorating salinity problems.

- The current reforestation programme on the Wellington Dam catchment is expected to reduce mean inflow salinities to below 1000 mg/L TSS by 2010. In the absence of clearing controls and reforestation, the inflow salinities would have reached 1500 mg/L TSS by this time.A planned integrated catchment management initiative should reduce stream salinities below those expected from the current reforestation programme.

- Commercial tree planting has the potential to accelerate the implementation of reforestation for salinity control.

- Integrated catchment management, involving the integration of water and land management, is seen as the best approach to future catchment rehabilitation.

- Specific management issues to be addressed are:
  - further clarification of salinity management priorities;
  - development and promotion of integrated catchment management systems that will maintain or enhance economic productivity and reduce stream salinity;
  - directing commercial tree plantations to areas of greatest salinity benefit;
  - assessment of the impact of salinity on conservation of lake and riverine ecosystems and implementation of rehabilitation measures;
  - development of management techniques to ensure the long term protection of remnant native vegetation on farms;
  - protection of forested catchments which are subject to forestry and mining operations, diseases and pests;
  - determination of social implications of various stream salinity reclamation measures.

- Specific future research requirements are to:
  - develop and assess reforestation and agricultural strategies within an integrated catchment management framework to control stream salinity;
  - develop viable and economically productive tree plantations for salinity control;
  - improve selection, breeding and establishment of trees on saline seeps;
  - assess and develop perennial pastures, crops, fodder trees and surface drainage to control salinity;
  - develop an improved capacity to model catchment rehabilitation strategies;
  - accurately predict the future time course of stream salinities;
  - determine the potential impact of climate change on stream salinity and water yield;
  - develop methods of identifying recharge areas and dolerite dykes.

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Appendix I : Water Resources Salinity Classification

Fresh	Less than 500 mg/L TSS
Marginal	Greater than 500 mg/L TSS but less than 1000 mg/L TSS
Brackish	Greater than 1000 mg/L TSS but less than 5000 mg/L TSS
Saline	Greater than 5000 mg/L TSS

Appendix II: 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
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