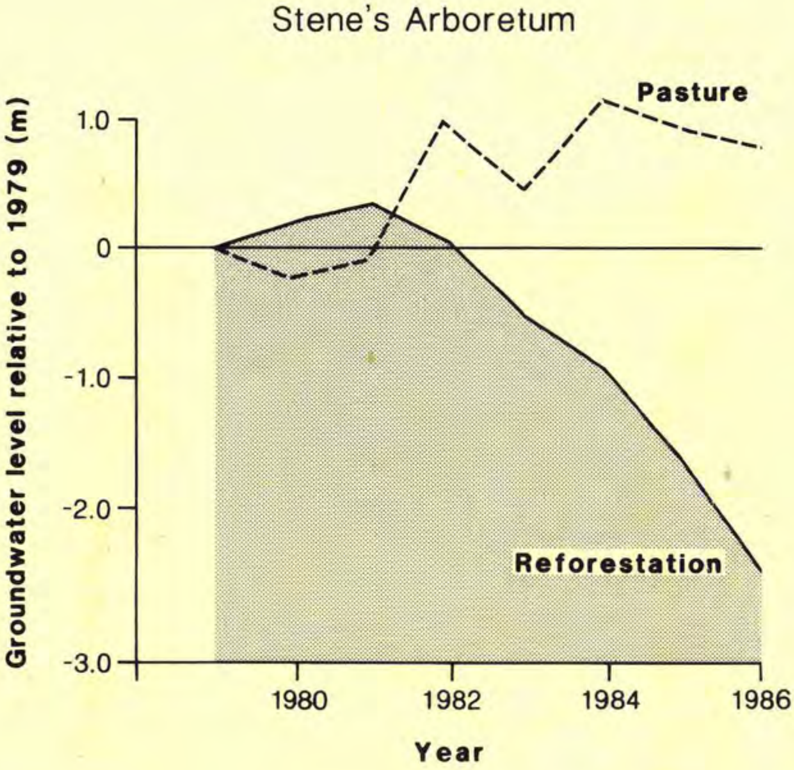
Vegetation Strategies to Reduce Stream Salinities of Water Resource Catchments in South-West Western Australia



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Vegetation Strategies to Reduce Stream Salinities of Water Resource Catchments in South-West Western Australia

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

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with assistance from the
Water Resources Catchments Rehabilitation
Subcommittee of the Steering Committee for
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Streamline Abstract

VEGETATION STRATEGIES TO REDUCE STREAM SALINITIES OF WATER RESOURCE CATCHMENTS IN SOUTH-WEST WESTERN AUSTRALIA

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The most cost-effective method of reclaiming high salinity water resource streams in south-west Western Australia is revegetation. Revegetation may take the form of replanting trees or establishing high-water using agricultural plants. Trials which commenced in the late 1970s have shown that partial reforestation can lower saline groundwater tables. The higher the proportion of cleared area replanted the faster the rate of water table lowering. Near total reforestation of a small catchment dramatically reduced its salt export.

Agricultural strategies, particularly in combination with partial reforestation, have considerable potential to ameliorate stream salinisation. These include the establishment of perennial pastures, fodder shrubs, fodder trees, agroforestry, higher water using crops and the use of appropriate surface drainage techniques.

A number of factors are now emerging that can significantly enhance stream salinity reclamation by revegetation. These are improved tree establishment techniques in saline-waterlogged sites; development of a commercial pulpwood industry for short-rotation tree cropping of reforestation; improved knowledge of higher water using agricultural plants; and an implementation framework of integrated catchment management.

Key words: Stream salinity, revegetation, reforestation, reforestation strategy, agriculture, water resources, groundwater, pulpwood, catchment, integrated catchment management, tree establishment, water use, transpiration, tree selection, recharge zone, discharge zone, reclamation, rehabilitation, agroforestry, surface drainage, fodder crop trees, agronomy, management, research, review.

Water Authority of Western Australia, Perth, 1989, ISBN 0 7309 1774 6, xvii 81 pp, 33 figures, 22 tables, Water Resources Directorate, Surface Water Branch Report No. WS 33.

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.
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.

Foreword

The salinisation of streams and land has been a growing problem in Western Australia since the turn of the century. However it was not until the 1960s that serious attempts were made to control the problem. The first control measures were to protect important marginal water resource catchments from further land alienation (release of Crown land to private landowners) and from further clearing of native vegetation - the principal cause of salinisation. These actions, while important and necessary, were not sufficient to prevent stream salinities increasing. This realisation led to the consideration of rehabilitation measures.

Research programmes on rehabilitation were established in the mid-1970s utilising expertise within State Government Agencies, CSIRO, and Tertiary Institutions. In 1979, the Public Works Department (now Water Authority of Western Australia) embarked on a forward looking reforestation programme to control the increasing salinity of inflow to Wellington Reservoir. This reforestation programme was developed progressively, relying directly on the emerging results of the research. Prompt transfer of knowledge was achieved as staff designing the reforestation programme were also leading major components of the research.

Co-ordinated and targeted research is continuing to guide developments in rehabilitation practice. Recent advances in rehabilitation include development of a range of agroforestry and agricultural salinity control measures, development of the commercial potential of reforestation and acceptance of the need for integrated catchment management to minimise water and land degradation while maximising land productivity, conservation and recreation values.

The comprehensive review of stream salinity reclamation research and management embodied in this report is, I believe, a most important and timely contribution to the state and national programmes to combat land and water degradation.

K. L. Barrett

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

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Summary

INTRODUCTION

Agricultural clearing in south-west Western Australia has led to substantial increases in the salinity of most rivers emanating from areas with less than 900 millimetres per year (mm/yr) rainfall. A range of methods for rehabilitating salt-affected streams and land have been investigated in the past. Those currently favoured include tree and shrub planting, agronomic manipulation and land drainage.

Tree planting strategies are widely regarded as potentially the most effective means of controlling stream salinity. This option is particularly attractive because only part of the agricultural land requires reforestation, allowing substantial agricultural production to continue, and because tree plantations could be economically viable in their own right.

Salinity control could also potentially be exerted through a combination of agricultural strategies. The rehabilitation technique for a particular catchment would in many cases be a mixture of reforestation and agricultural manipulation, the extent of each depending on the management objectives for that catchment.

This report evaluates the effectiveness of a number of reforestation and agricultural strategies in controlling groundwater level and stream salinity. The report concludes with the identification of management issues and future research needs.

REFORESTATION STRATEGIES

This major section of the report covers tree selection and establishment, comparison of four different reforestation strategies, reforestation area and density requirements, and commercial aspects of reforestation. The locations of the sites mentioned are shown in Figure 7.

Tree selection

The initial criterion for tree selection is adaptation to the environment. In the south-west this should include adaptation to climate, soils, pests, diseases, fire, and in some locations waterlogging and salinity. Adaptation to a given site will vary at the genus, species, provenance and individual tree levels.

Having satisfied the adaptation criterion, the other two main criteria are commercial value and water use. The commercial value of species has been easier to determine and there are good data on a number of *Eucalyptus* and *Pinus* species.

Knowledge of the water use capacity of various species could allow trees to be selected to maximise the effectiveness of reforestation or minimise the area of agricultural land required for reforestation. This characteristic, however, has been difficult to determine.

Only a few species have so far been identified which are adapted to waterlogging and salinity (saline seep) conditions. These include swamp sheoak (*Casuarina obesa*) and three eucalypts, salt river gum (*E. sargentii*), river red gum (*E. camaldulensis*) and swamp yate (*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. Glasshouse and field screening trials should identify other species and provenances adapted to salt/waterlogging stress.

For well drained soils, away from saline seeps, a wide range of suitably adapted species have been identified. Several are considered to have commercial potential. These include *Pinus radiata* for provision of timber and other wood products and the fast growing Tasmanian blue gum (*E. globulus*), manna gum (*E. viminalis*), southern mahogany (*E. botryoides*) and Sydney blue gum (*E. saligna*) for pulpwood production.

Tree establishment

Ways of establishing trees are by natural regeneration, direct seeding and planting of seedlings or clonal (vegetatively propagated) plants. Planting is the most reliable technique. In Australia seedlings are usually planted and that is the technique used in the Wellington Dam catchment reforestation project. In that project site preparation of all sites includes ripping and herbicide spraying for pasture (weed) control prior to planting in June or July. Seedlings are fertilised once, either at the time of planting or within two months of planting. In saline seep areas, where the trees are subject to salt and waterlogging stresses, seedlings are planted in ridge mounds. However the standard mounds (15–20 cm high) are generally inadequate to allow tree establishment in core areas of saline seeps even with salt/waterlogging tolerant trees. Recent research results indicate that establishment success can be improved by forming double ridge mounds and planting in the trough between the ridges.

Lower slope and discharge zone planting strategy

Reforestation trials have been conducted at two sites using this strategy. At the first site, Stene's Valley Plantings, 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 5400 milligrams per litre Total Soluble Salts (mg/L TSS). Over the period 1979–86 there has been a lowering of the groundwater table beneath the reforestation of 0.8 metres, whilst under pasture the groundwater level rose by 0.8 metres.

At the second site, Maringee Farms, 22% of the cleared area was replanted with *E. wandoo*, *E. camaldulensis*, *E. saligna* and numerous other species in 1981/82. At this site the highly saline groundwater table (15 600 mg/L TSS) was at a shallow depth of about one metre in the valley area. Tree survival rates were poor. Over the period 1982 to 1986 there was a lowering of the groundwater level below reforestation of 0.25 metres, whilst under midslope pasture the groundwater level rose by 2.0 metres.

Wide-spaced plantations

Reforestation in which trees are thinned to 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, *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 1978–86 the groundwater level beneath the reforestation declined by 1.8 metres while over the same period groundwater under pasture at a nearby site rose by 0.1 metres.

At Stene's Agroforestry, *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 1981–86 averaged over the whole reforested area has shown a net decline of 0.8 metres while under pasture at an adjacent site the groundwater level rose by 0.8 metres.

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 pasture. This layout was replicated five times. Tree species were planted according to salinity hazard. *Eucalyptus 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 depressed 0.25 metres. Measurement of soil salt content showed that, under reforested areas, salt content decreased over the depth range 0–0.75 metres, increased over the depth range 0.75–2.25 metres and remained the same below 2.25 metres. Under pasture there was little change in the salt content profile.

Strip and Landscape 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, 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 1979–86 there was only a slight depression of groundwater level beneath reforestation of 0.2 metres, while beneath pasture there was a small rise of 0.1 metre.

On the Stene's Strip site, 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 1978–86, the groundwater levels under the strips rose on average by 0.2 metres, whilst under pasture the groundwater level rose by 0.8 metres.

The Bannister site 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 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.

Intensive Plantations

Intensive 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.

Flynn's Hillslope 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 two metres over the period 1978–86 while there was little change in groundwater level beneath pasture over the same period.

At Stene's Arboretum 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 1979–1986 there was a net lowering of groundwater level under reforestation by 2.5 metres, while under pasture at a nearby site groundwater levels increased by 0.8 metres.

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. 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 unchanged. The lack of a decrease in stream salinity may be partly attributed to a small incised area (approximately 4% of the catchment) adjacent to the main stream being left 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 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 quantity of fresh water inflow and increase the catchment discharge salinity.

Reforestation area and density

The effectiveness of the various reforestation strategies in reducing groundwater level beneath plantations of age 7–10 years has been found to depend primarily on the area and density of trees planted, rather than the particular strategy. A regression of average rate of water table reduction against proportion of cleared area reforested indicates that reforestation of 11% of the cleared area was required to maintain groundwater levels beneath reforestation at a constant level relative to the grouund surface over the experimental period. To achieve a lowering of the groundwater level at a rate of 200 mm/yr would require reforestation covering 46% of the cleared area. Rainfall over the measurement period was 10% less than the long-term average. If rainfall had been the long-term average, the area of reforestation required to achieve a 200 mm/yr groundwater level reduction would probably be significantly greater than 46%.

A slightly improved regression was obtained when average rate of water table reduction was regressed against the product of proportion of cleared area reforested and crown cover. This result could imply that total tree cover is the most important factor in the lowering of the water table beneath reforested areas.

Groundwater salinity beneath reforestation

In the past concern has been expressed about the potential of salt concentration to increase beneath reforestation stands and affect their long term viability. At Flynn's Farm and Stene's Farm (~ 700 mm/yr rainfall) the groundwater salinity beneath reforestation has decreased on average (geometric mean of bores) by 11% over the period 1979–86. Under pasture at these sites the groundwater salinity has decreased by 43% over the same period. At Boundain (~ 500 mm/yr rainfall) groundwater salinity has decreased under pasture but increased under reforestation. There is no clear explanation of the different groundwater salinity responses at the above sites, although rainfall may be a factor.

Commercial Aspects of Tree Plantations

An economic analysis of *P. radiata* forestry in the Manjimup region found that it could be very competitive with grazing. 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 its intention to establish a 'Tree Trust' to develop a pulpwood cropping industry.

Agroforestry also appears to be commercially attractive. It allows substantial returns from agriculture to be maintained while trees are growing. Such wide-spaced methods of tree growing may also enable timber production to be extended to lower rainfall areas where extensive, dense plantations may not survive.

Field trials involving wide-spaced eucalypt plantations have shown that some species have fast growth rates and suitable form. The natural tendency of eucalypts to self-prune greatly reduces the cost of pruning compared with pine.

AGRICULTURAL STRATEGIES

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 grasses. This could be partly explained by its shallower rooting depth.

Of the perennial pasture species, lucerne has been shown to transpire large quantities of water. Phalaris and other perennial grass species also have promising transpiration characteristics. Over 500 000 ha of present agricultural land is considered suitable for perennial grasses, principally in the southern agricultural areas. More work is required, however, on their adaptation, productivity and persistence.

Crops of lupins, oats and barley have all been found to have higher water use than annual pastures. The water use of crops could be maximised by optimising time of sowing, fertiliser application and minimising waterlogging.

Surface drainage

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

Shallow interceptor drains have been shown to discharge significant amounts (2–18% of rainfall) of surface and shallow perched water. 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 adding fresh water to streams or by reducing groundwater recharge. Interceptor drains which do not effectively discharge water could increase groundwater recharge and hence increase stream salinity.

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 levels of transpiration. Its agricultural value is clear when compared to annual pasture production on deep, infertile sands, but is yet to be quantified relative to good quality annual pastures on more fertile soils. Further research is required on this species, and a number of other fodder trees that are well adapted to local conditions.

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 in low rainfall (less than 500 mm/yr) areas.

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 water and land management and the associated agencies and community to solve specific environmental problems. The integrated catchment management approach has been adopted by the Western Australian government and is being implemented in the Denmark River catchment with the objective of reducing stream salinity but 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 bring about the required solution.

On the Wellington Dam catchment, the reforestation programme initiated in 1979/80 is to continue to the early 1990s. A major review is underway to develop a new catchment management strategy to restore the whole water resource to potable levels in the foreseeable future. The envisaged rehabilitation programme is likely to incorporate the integrated catchment management approach being tested on the Denmark catchment.

MANAGEMENT ISSUES

- 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 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.

- The establishment of broad scale commercial tree plantations on farmland in the higher rainfall areas (greater than 900 mm/yr rainfall) could significantly reduce fresh water yield and increase stream salinity of large catchments. Means of directing plantations to lower rainfall areas where they would reduce salt discharge should be developed.

FUTURE RESEARCH REQUIREMENTS

- 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 evaluations.
- Research should be continued to select, breed and establish trees for planting in and adjacent to saline seeps.
- The hydrologic performance of species selected for growing in and adjacent to saline seeps should be evaluated.
- A better understanding of salt dynamics beneath reforestation to determine the potential for salt accumulation and to assess its effect on reforestation is required.
- The potential of perennial pastures as a salinity control measure requires evaluation.
- A fodder tree screening programme should be undertaken and the salinity control potential of promising species evaluated.
- Further evaluation of the potential of shallow surface drains as a salinity control measure is required.
- Investigation of broad-scale survey methods to identify high recharge areas and potentially seep forming dolerite dykes is necessary.
- An improved modelling capability to predict the effectiveness of various vegetation strategies in controlling stream salinity requires development.

CONCLUSIONS

- 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 product of area reforested and crown cover. To achieve a useful rate of water table reduction in the 700–800 mm/yr rainfall zone under current rainfall conditions, about 45% of the cleared land should be reforested with dense plantations, or nearly all the cleared area reforested with wide-spaced plantations. Under long term average rainfall conditions this figure may be significantly higher.
- To eliminate salt discharge 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 a small 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 help 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 inflow salinities to below 1000 mg/L TSS by 2010. A planned integrated catchment management initiative would lower this further. In the absence of clearing controls and reforestation, the inflow salinities would have reached 1500 mg/L TSS by this time.
- 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:

—development and promotion of integrated catchment management systems that will maintain or enhance economic productivity and reduce stream salinity;

—development of a role for remnant native vegetation on farms within the context of integrated catchment management while also addressing the question of biological conservation;

—investigating measures to control the escalating insect problem in the jarrah forest;

—directing commercial tree plantations to areas of greatest salinity benefit.

- Specific future research requirements are to:

—develop viable and economically productive tree plantations for salinity control;

—improve selection, breeding and establishment of trees on saline seeps;

—assess and develop perennial pasture species, crops, fodder trees and surface drainage to control salinity;

—develop methods of identifying recharge areas and dolerite dykes;

—develop an improved capacity to model catchment rehabilitation strategies.

1. Introduction

The impact of agricultural development on the salinity of water resources in the south-west of Western Australia has been dramatic (Steering Committee for Research on Land Use and Water Supply, 1988). Recent updating of the water resources inventory (Western Australian Water Resources Council, 1986) indicates that 36% of the divertible surface water resources of the South-West Drainage Division have salinities in excess of 1000 mg/L TSS (brackish or saline). A further 16% are of marginal quality (500 to 1000 mg/L TSS) and only 48% remain fresh (less than 500 mg/L TSS). Prior to agricultural development virtually all the divertible surface water resources of the region would have been fresh.

The relationship between clearing native vegetation for agriculture and the subsequent increase in stream salinity has been clearly demonstrated by research over the last 20 years although the first observations of the effects were reported early in the century (Wood, 1924). The permanent removal of deep-rooted vegetation and its replacement with annual shallow-rooted crops and pastures has led to an increase in groundwater recharge. Consequently, groundwater levels have risen, leading to increased groundwater discharge to surface streams. Increases have also occurred in the quantity of shallow subsurface flow (throughflow) and surface runoff contributing to streamflow. The overall effect on stream salinity is a complex function of the quantity and particularly the salinity of the additional groundwater discharge, as well as the quantity and quality of the additional throughflow and surface runoff. However, stream monitoring in south-west Western Australia has shown that clearing always results in increasing stream salinity in areas with rainfall less than 1100 mm/yr.

In high rainfall (greater than 1100 mm/yr) areas of the Darling Range only small quantities of salts have accumulated in the soil. In these areas groundwater salinities are fresh and the impact of agricultural development on stream salinity is low.

In rainfall areas between 900 mm and 1100 mm, moderate levels of salts are present in the landscape and, if mobilised by forest disturbance, can cause significant increases in stream salinity. However, few areas of this rainfall zone have been developed for agriculture and consequently little salinity deterioration has been observed.

In the region below 900 mm annual rainfall, large quantities of salts are present in the landscape and major agricultural development has taken place. This combination of agriculture and high soil salt storage has led to substantial increases in stream salinity (Steering Committee for Research on Land Use and Water Supply, 1988, Table 8).

River systems which drain extensive wheatbelt areas with annual rainfalls of less than 600 mm/yr have become so saline they are no longer usable as potable water resources. River systems which drain areas which do not extend further inland than the 600 mm annual rainfall isohyet are generally of marginal or brackish quality and are high priority areas for protection and improvement of their water quality. Consequently much of the current water resources research in Western Australia is aimed at reducing stream salinity in the 600 mm to 900 mm rainfall zone of the south-west of the State.

Agriculture has not only brought about substantial increases in stream salinity, but has caused significant land salinisation in south-west Western Australia (e.g. Malcolm, 1983). A survey to gauge the extent of agricultural land affected by salinity in 1984 found that 255 000 ha or 1.6% of agricultural land was severely salt-affected (Australian Bureau of Statistics, Perth, pers.comm. 1988). The average rate of increase in salt-affected land in this region since 1955 has been about 6000 ha/yr. Reclamation of salt-affected land is naturally relevant to reclamation of salinised streams, but the approaches may be different because of different objectives and economic considerations.

Stream and land salinisation are not confined to Western Australia, but affect several arid and semi-arid regions of the world. Increasing salinity of irrigated soil is a problem going back 4500 years to Mesopotamian times (Jacobsen and Adams, 1958) and today affects about one-third of the irrigated land around the world (Reeve and Fireman, 1967). In Australia some 426 000 ha of non-irrigated land and 123 000 ha of irrigated cropland are affected by soil salinity induced by human activities (Peck *et al.*, 1983). According to recent estimates, 600 000 ha of irrigated cropland in Victoria and New South Wales have water tables within two metres of the soil surface (Grieve, 1987). The economic impact of salinity could treble within 30 years without the implementation of effective control measures (Salinity Committee, 1984).

In the United States the total area of salt-affected soils has been estimated at 45 million hectares (McKell *et al.*, 1986). An estimated 810 000 ha of the northern Great Plains in the United States and Canada are affected by dryland salinity (Brown *et al.*, 1983). Of the 4.1 million hectares of farmland irrigated in California, about 30% are affected by salinity (Backlund and Hoppes, 1984). Soil salinisation has been estimated to affect 20–25% of all irrigated land in the United States.

A range of methods of reclaiming salt-affected land and water resources has been investigated in the past. These can be divided into engineering solutions such as pumping of aquifers or land drainage, and biological solutions such as tree planting or agronomic manipulation. In recent years biological solutions have gained prominence. A wide range of potential strategies exist but there have been few studies of the effectiveness of particular strategies. This report describes and evaluates in some detail the various vegetation strategies that have been investigated in Western Australia.

2. *Concepts and Factors in Vegetation Strategies*

2.1 The Potential of Vegetation to Control Salinity

A large part of the world's dryland salinity occurs as an indirect result of the reduction in the quantity of water evaporated by vegetation. In south-west Western Australia the main cause has been the replacement of native vegetation (largely forest and woodlands) with annual agricultural species. Amongst other things this agricultural development has led to groundwaters rising and contributing excessive quantities of salt to streams. One approach to controlling stream salinity is to reverse the above process by increasing evaporation from the agricultural land. This may be achieved by revegetating selected areas with higher water using, non-agricultural plants or by changing agricultural species and practices.

The use of trees and other perennial plants to control groundwater recharge and discharge has been a subject of interest and investigation for some years (Greenwood, 1978, 1986; Morris and Thomson, 1983). The ways in which revegetation can increase evaporative discharge are by increasing annual interception loss and transpiration. The environmental conditions in salt-affected parts of the landscape are considerably harsher for vegetation than non-saline areas. These sites usually occur in the lower landscape and are often characterised by the combination of high salinity and waterlogging. The opportunity for revegetation to increase evaporative discharge in these harsh sites requires successful species selection and establishment.

The main factors affecting the design of vegetation strategies for the reclamation of salt-affected streams and land are environmental conditions, species, area planted, plant density and distribution in the landscape, economic considerations and management requirements. These factors are discussed in the following sections.

2.2 Environmental Conditions of the South-West Region

2.2.1 Hydrogeological conditions

The selection of a particular vegetation strategy for salinity control may depend on local hydrogeological conditions. This is exemplified by comparing south-west Western Australia, where salinity problems are usually associated with local ($\lesssim$ 1 km) groundwater systems, with northern Victoria, where groundwater recharge in the uplands discharges some 200 km away on the Loddon Plain (Macumber, 1978).

In the south-west region the most important surface water resource catchments are located in the Darling Range. Here the geology influences the behaviour of the groundwater system, which in turn plays a major role in stream salinisation. The Darling Range is delimited in the west by the Darling Scarp, which marks the western margin of the Great Plateau of Western Australia (Jutson, 1914). Geologically, the Darling Range forms part of a stable Archean shield composed largely of granite which has invaded linear belts of metamorphosed sedimentary and volcanic rocks, some isolated occurrences of which remain. Thin sheet-like dolerite intrusions occur abundantly in the basement rock, particularly near the Darling Scarp where they may constitute up to 30% of the basement (J. Croton, pers. comm. 1988). Weathered and unweathered dolerite dykes are known to affect groundwater movement and have been implicated in the development of hillside seeps (Engel *et al.*, 1987).

Drainage is progressively less entrenched on passing from the Darling Scarp into the inland areas. Close to the Scarp, deep V-shaped entrenchments occur with shallow soils and frequent rock outcrops. Local relief is often in excess of 200 m. Valley side slopes are as steep as 35%, but of short length (~300 m). Next in progression inland are U-shaped valleys with local relief about 50–150 m. These are succeeded inland by valleys which form broad entrenchments in the undulating upland surface, with local relief rarely greater than 50 m. The valley sides have inclinations less than 10% but often extend 1–2 km in length. This inland surface is extensively laterized and the weathered mantle is in places more than 50 m deep.

The groundwater hydrology of the Darling Range is characterised by a two-aquifer system. This consists of an ephemeral unconfined aquifer in the coarse-textured surface soils perched on a fine-textured B horizon, and a semi-confined or unconfined perennial aquifer residing in the deeper saprolite above the bedrock. It is generally agreed that the deep aquifer plays the major role in the development of saline seeps, which are associated with groundwater discharge areas.

Discharge areas occur predominantly in the valley floors, but hillside seepages also occur (Nulsen, 1985). In the broader valleys, seeps could potentially cover 20–25% of the land surface where near total clearing has taken place (Hookey and Loh, 1985a; Hookey, 1987).

2.2.2 Vegetation conditions

In its pristine condition the vegetation of the low rainfall (600–900 mm/yr) zone of the water catchments could be divided broadly into two structural classes after Smith (1974) i.e. the open-forest of jarrah–marri *(Eucalyptus marginata-E. calophylla)* and the woodland of wandoo *(E. wandoo)*. Within these two broad groupings various workers (Havel, 1975 a, b; Heddle *et al.*, 1980; Strelein, 1988) defined some 20 site-vegetation types which occur along a continuum of variation in understorey composition and overstorey productivity. They also demonstrated that this variation in vegetation reflected the combination of site characteristics arising from systematic trends in geomorphology (affecting soil type and fertility) overlain by the west to east and south to north decline in rainfall.

Jarrah forest types predominate on the deeper, more freely draining sites which have greater soil water storage. They are more extensive in the wetter western and southern parts of the zone. Wandoo types occur on profiles which are shallow or have impeded drainage and are prone to seasonal waterlogging. These are most common in low landscape positions in the eastern part of the zone. Havel (1975b) considers it most likely that the jarrah/wandoo boundary occurs where inadequate soil moisture storage is available to support jarrah.

Agricultural development is the most extensive disturbance to which south-west catchments have been exposed. It involves nearly complete eradication of the native vegetation. The soil is physically disturbed and may be compacted. Although this may reduce the surface infiltration capacity, a considerable increase in soil water storage occurs due to water infiltrating below the root depth of the introduced agricultural species (Sharma *et al.*, 1987). The subsequent increased recharge to groundwater has caused water tables to rise and mobilise salt previously stored in the unsaturated zone. This has created saline seeps in valley floors and on some hillslopes. These seeps may locally occupy up to 25% of the land area.

Major changes to the natural environment associated with agriculture compromise the use of native species for revegetation. The use of fertiliser together with legume-based pastures (mainly *Trifolium subterraneum*, sub clover) increases soil fertility which probably renders natural fertility variations irrelevant. The vigour of the annual pasture species inhibits the natural recolonisation of pasture land by native species. The extensive all-weather use of agricultural machinery has probably resulted in the widespread distribution of the soil borne fungus *Phytophthora cinnamomi*, the pathogen responsible for jarrah dieback (Podger, 1972).

Bartle and Shea (1978) considered the general problem of disturbance to water catchments throughout the south-west, including that due to mining and forest disease, and concluded that a comprehensive species introduction and testing programme was required to identify species for revegetation.

2.2.3 Hydrologic and salinity characteristics

The surface water catchments of marginal water quality, while having increasing stream salinity, still have potential for water resource development. These catchments have similar hydrological features. The catchments extend from the coast inland to, or just beyond the 600 mm/yr rainfall isohyet. In the high rainfall region they are characterised by high volume, low salinity yields, whereas the reverse holds under low rainfall. Typically 80% of the total salt load but less than 30% of the total streamflow volume is generated from the agriculturally developed land with less than 900 mm mean annual rainfall.

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. Land uses which reduce flow volumes in the high rainfall areas are likely to increase the salinity of these water resources and should be discouraged.

2.3 Plant Selection

The main criteria for selecting plants for controlling saline groundwater discharge are adaptation to the environment; high water use to give rapid and sustained depression of groundwater tables and/or reduction of groundwater recharge; and, where possible, secondary benefits such as providing timber, pulpwood, agricultural produce or conservation values. With increasing refinement of the selection process, plant selection for a particular need tends to progress from selection at the genus or species level to selection of the best provenance, cultivar or individual (clone) of a desirable species.

2.3.1 Adaptation to the environment

Several major features of the south-west environment demand particular adaptation in the plants to be introduced (Bartle and Shea, 1978, 1979). These include climate, soils, pests and diseases, fire, waterlogging and salinity.

Perennial plants must be able to tolerate the seasonal drought (only 20% of the annual rainfall occurs during the six months from November to April).

The soils are often infertile and some of the valley floors are characterised by extensive hard pans.

Plants should be adapted to the common diseases and pests which include the fungi *Phytophthora cinnamomi* and *Armillaria luteobubalina*; and the insect pests leaf miner (*Perthida* spp) and gum leaf skeletonizer *(Uraba lugens)*.

Long-living plants such as trees and shrubs are likely to be subject to fire and should be adapted to either wildfires or routine prescribed burning.

Some revegetation strategies involve planting on or adjacent to saline seeps. Saline seeps are often the most difficult areas to revegetate due to combined waterlogging and salinity stresses. These areas present quite specific species selection and establishment requirements (see section 3.1). Upslope but adjacent to saline seeps, the presence of a relatively shallow (around 5 m or less) saline water table also requires specific adaptation features. The main limiting condition is the small depth of unsaturated zone and consequently small unsaturated soil water storage available for transpiration. Phreatophytes (plants directly tapping the groundwater) capable of transpiring moderate to high salinity groundwater may be necessary in this area.

2.3.2 Plant water use

For revegetation to lower groundwater levels (and hence stream salinity), water balance considerations imply that the total evaporation from the landscape with revegetation must exceed that which occurred under native conditions. The total evaporation from the landscape with revegetation will depend on the proportion and location of native vegetation, agricultural land and revegetated land and their respective evaporation rates. Since the potential evaporation of native forest exceeds annual rainfall in the 600–900 mm/yr rainfall zone, it is not necessary to reforest all the agricultural area to utilise the annual rainfall. The greater the amount of tree cover in excess of that needed to utilise rainfall, the greater will be the rate of reduction of the groundwater table.

The area of reforestation can be minimised by selecting high water using trees, that is trees with high annual transpiration and interception loss. Thus, of the species adapted to the site conditions it can be advantageous to select trees with the potential for high water use.

2.3.3 Benefits other than salinity control

The major secondary benefit of reforestation to control salinity is wood products such as sawlogs, fence posts, and pulpwood. Providing that trees are adapted to the specific environment and have high water use, then selection of species on the basis of their commercial potential can be an important criterion. Where the commercial potential of timber is competitive with agricultural production, there is scope for replanting a greater proportion of the agricultural land. Commercial tree plantations are also attractive to farmers as a means of diversifying their income. Alternatively, where reforestation for salinity control involves land purchase, the cost can be significantly discounted if commercial trees can be planted.

Other secondary benefits to reforestation can include livestock shade and shelter, wind erosion control, providing a habitat for fauna and the production of honey and eucalyptus oil.

2.3.4 Summary of plant selection criteria

Plant selection should firstly be on the basis of adaptation to the environment. In catchments which are partially salt-affected, this would generally involve different groups of plants being selected for different positions in the landscape. Within these groups, plants can be selected for high water use and commercial value. The commercial criterion is generally easier to quantify (see section 3.1) and may become a more significant criterion. The ideal plants have both characteristics. The relative importance of plant selection criteria are likely to change over time in response to changing environmental conditions and economics.

2.4 Area of Reforestation

As mentioned in section 2.3.2, area of reforestation is critically important to the level of impact revegetation will have on groundwater levels and consequently on stream salinity. This problem is discussed in detail in section 4.1.

2.5 Tree Distribution

Several strategies for planting location and density have been considered. These strategies are based, as much as possible, on preserving the commercial productivity of the land by integrating reforestation with agriculture. They usually include some of the following elements, five of which are located in the groundwater recharge zone and one in the groundwater discharge zone:

(a) dense planting of trees in areas with high recharge rates within the recharge zone;

(b) dense planting of trees strategically placed in blocks or strips in the recharge zone;

(c) low density planting of trees throughout the cleared portions of the recharge zone;

(d) planting of relatively high water using crops or pastures, preferably deep-rooted and perennial, in the recharge zone;

(e) dense planting of trees in the lower landscape just above the discharge zone;

(f) planting of salt and waterlogging tolerant trees, shrubs or herbs in the discharge zone.

These elements of a vegetation strategy are discussed in the following subsections. Particular strategies involving combinations of these elements are discussed at length in Section 3.

2.5.1 Dense tree planting of high recharge areas in recharge zone

The basis of this approach is to identify high groundwater recharge areas and densely plant them with trees to minimise the recharge. One of the main problems is the identification of high recharge areas. In the landscapes developing secondary salinity in northern USA the distribution of recharge areas is highly complex (Brown *et al.*, 1983). The same is true in southern Australia (Williamson, 1986). In Western Australia, Johnston (1987) found that recharge rates were highly variable over small distances (tens of metres). Morris and Thomson (1983) claim that it should be possible to identify major recharge areas by stratifying catchments according to rainfall, vegetation, slope, aspect and soil type, combined with existing knowledge of groundwater resources. Recent attempts at defining recharge (and discharge) areas have focused on electromagnetic and magnetic surveying (Williams and Hoey, 1987; Engel *et al.*, 1989). These methods have been successful in defining upland recharge areas and discharging seeps immediately upslope of weathered dolerite dykes in one small catchment (Engel *et al.*, 1989). The electromagnetic technique has the potential to rapidly survey salt storage and recharge areas but the relationships between electromagnetic signal, salt storage and recharge require better definition. In particular the relationship of salt storage to recharge is not always straightforward (George, in press).

2.5.2 Strip or block tree planting in recharge zone

In this and the following approaches, identification of localised high recharge areas is ignored. The aim is simply to plant an adequate number of trees to control groundwater levels, while having a system suitable for managing both agriculture and forestry.

One strategy is to plant strips of trees parallel to the streamline. Peck (1976) discussed the spacing of such strips of phreatophytic trees. Trees would need to be planted in areas where the groundwater table is within about five metres of the surface to efficiently utilise the groundwater (J.K. Marshall, pers. comm. 1988). Another strategy is to plant irregular shaped blocks of trees on areas thought to have most control over seeps on hydrogeological grounds.

2.5.3 Low density tree planting in recharge zone

Low density (wide-spaced) plantations is an alternative agroforestry strategy to the one described above. The practicality and economic viability of this strategy has been well researched in Western Australia and is described in detail in section 3.3. This approach is well suited hydrologically to lower rainfall areas with limited soil water availability.

2.5.4 High water using agricultural plants in recharge zone

Increases in groundwater recharge resulting from replacement of native vegetation by agricultural crops are considered to be of order 10–100 mm/yr. These relatively low values have promoted the idea that higher water using crops, especially perennial species, may be sufficient to control saline seeps. This has indeed been the case on the northern Great Plains of the USA where replanting 80% of the recharge zone with lucerne (*Medicago sativa*) has been successful in reclaiming saline seeps. Assessments of the potential of agronomic strategies for recharge control have been made in Western Australia and are described in section 5.

2.5.5 Dense tree planting on lower slopes just above discharge zone

The objective of dense planting on the lower slopes is to reduce water movement, particularly groundwater movement, into the discharge or seep area. Such plantations would reduce recharge to groundwater on the lower slopes, intercept groundwater moving downwards from upslope areas, and may also lower groundwater levels in the discharge zone itself. De-watering the perimeter of the seep could allow progressive reclamation of the seep area with progressive planting.

The depth to groundwater beneath lower slope plantations would be of order 2–5 metres and groundwater salinities can be high. Thus trees would need to be specifically adapted to this environment.

2.5.6 Tree or shrub planting in discharge zone

The strategy of only revegetating saline discharge areas as a means of reclaiming seeps or eliminating salt discharge to streams has been strongly criticised (Conacher, 1982; Morris and Thomson, 1983; Williamson, 1986). It is argued that groundwater solute concentration would increase as a result of transpiration of water but not salts, and from the inflow of solutes to the discharge area. Increasing salt concentration in the root zone and increasing salinity of the groundwater used by plants could affect the long term viability of discharge zone revegetation. Furthermore Morris and Thomson (1983) suggested that localised plantations would not be adequate to control high regional water tables because new seeps may form outside the range of the plantations. They also noted that plantations overlying semi-confined aquifers may not be able to penetrate the confining pans, which would make control of saline discharge impossible.

Morris and Thomson (1983) suggested that the establishment of trees in discharge areas could be useful when combined with recharge control measures. The high annual water use and deep rooting habits of trees, and the ability of some trees to draw on groundwater, would lead to more rapid lowering of water tables than may be possible otherwise. If recharge control was practised at the same time, it should be possible to stabilise the water table at a depth sufficient to eliminate discharge of salt to the surface. Any increase in groundwater salinity would be of limited significance because it would no longer be necessary for vegetation to extract groundwater.

2.6 Economic Aspects of Salt Reclamation

Economic considerations may apply significant constraints to the potential for reclamation of salt-affected areas. In most of the tree planting strategies described previously there would be a conflict with agriculture. In financial terms, agricultural returns would be weighed against returns from potential timber production, reclamation of water resources, increased agricultural production from previously salt-affected areas etc. An economic analysis would necessarily be time-dependent due to such factors as the potential effect of increased salinisation in the absence of reclamation measures, the time taken in reclamation and projected trends in returns from agriculture, timber and water. Clearly, on economic grounds, reclamation strategies would vary depending on the particular situation. For example, in Western Australia crucial water resource catchments would attract more extensive reclamation measures than purely agricultural catchments.

Some authors who favour recharge control strategies, but do not desire to impair agricultural production (e.g. Morris and Thomson, 1983), propose selective tree plantings which cover only a small portion of a catchment. While such plantings may provide a minor benefit in salinity control in Western Australia, it will become clear, in this report, that more substantial areas of the landscape require planting if reforestation is to be successful as a salinity control measure.

A number of tree planting strategies have now been developed that employ commercial species, and when combined with agriculture should allow an economically attractive solution. Salt/waterlogging tolerant species with little or no commercial value will be required for discharge zones in the early years, but could possibly be replaced by commercial species once groundwaters had been significantly lowered.

2.7 Approaches to Catchment Rehabilitation

VICTORIA

The State of Victoria has been active in proposing approaches and testing strategies aimed at controlling salinity through reforestation. Morris and Thomson (1983) put forward suggestions of how trees could be planted on farmland without reducing agricultural productivity. In their words: 'The aim should be to plant as many trees as possible, without reducing agricultural productivity. There are undoubtedly many opportunities for tree planting within this constraint on most Victorian farms, and on public land in agricultural districts. Possibilities include roadsides, easements, reserves, land too steep, stony or boggy for economic agricultural use, and around homesteads. To these may be added deliberate commitments of farm land for tree growing for a specific purpose, including shelter belts and woodlots producing firewood, round timbers, pulpwood or sawlogs. In every case, benefits will accrue to the landholder and the local community, not only through salinity control but by providing shade, shelter, landscape amelioration and wildlife habitat in addition to harvestable tree products.'

In the Loddon-Campaspe region of north central Victoria, Project Branchout set out to revegetate sites affected by salinity and soil and wind erosion. The project was based on a strategy described by Oates (1983). Over the period 1984 to 1986, over 120 000 trees were planted on 60 sites. The aim was to select demonstration sites with some form of degradation which had high public visibility and involved farmers, schools and community groups. Species planted included acacias, casuarinas, eucalypts and melaleucas. Plantings were located along road reserves, drainage lines, field borders and on lower slopes. Aesthetic values were improved by varying species composition, area of planting and spacing between planting units.

The main objective of Project Branchout was to increase public awareness of the value of tree planting to enhance environmental and aesthetic values in rural areas. Practical information on species survival and early performance, preparation, maintenance and costs was compiled. On-going monitoring was not an objective. The success of the project could be assessed in the number of private plantings that occur as a result of the demonstration sites.

Another large-scale demonstration project in Victoria is the Potter Farmland Plan. The concept is based on whole farm planning which includes farm layout, management and revegetation (Campbell, 1987a). A base map of the property which shows natural features, fencing, water supplies, structures etc. is drawn first. A new plan of the entire farm is then prepared according to several design principles: fencing to exclude stock from watercourses, non-arable areas and saline seeps; designating land use according to its capability; sowing of new perennial pastures; and tree planting to control wind erosion, reduce groundwater recharge and provide timber, fodder and wildlife habitat. One of the objectives is to increase plant water use over as much of the farm area as possible.

Farm planning and revegetation has been implemented on 15 farms in three areas of Western Victoria near Hamilton. About 100 000 trees have been planted (Campbell, 1987b). Trees have been planted as shelterbelts, agroforestry combinations of widely-spaced trees with pasture or crops, farm woodlots, fodder shrub reserves, circular fenced clumps and scattered individual trees in pasture. Salt-tolerant perennial grasses were planted in salinised areas. As with Project Branchout, the main objective of the Potter Farmland Plan is to demonstrate to other farmers the benefits of whole farm planning and complementary revegetation.

WESTERN AUSTRALIA

In Western Australia a major reforestation programme was commenced in 1979 by the State Government in the Wellington Dam catchment to halt its rapidly increasing stream salinity. To 1989, 5737 hectares of farmland have been planted. The reforestation strategy involved planting discharge areas and the adjoining lower slopes of the recharge zone, leaving middle and upper slopes for the continuation of agriculture. The cost of purchasing farmland was about $6 million and $3.4 million has been spent to date on planting over four million trees.

The process of land purchase and reforestation is slow and expensive. New approaches to catchment rehabilitation are now being developed through integrated catchment management. In this approach the relevant State agencies for water and land management, together with landowners and the community, develop an integrated approach to solve salinity and other environmental problems. This involves extensive land capability mapping and the implementation of combined reforestation and agricultural strategies. There is now significant potential for commercial reforestation of farmland which would substantially improve the cost-effectiveness of catchment rehabilitation.

3. Reforestation Strategies

3.1 Tree Selection and Establishment

Appropriate trees (or trees and shrubs) must be selected for reforestation. The main criteria for selecting any plants for saline groundwater discharge control are given in section 2.3; i.e.

(i) adaptation to the environment

(ii) desirable water use characteristics and

(iii) provision of benefits other than salinity control.

In this section the selection of trees according to those criteria is discussed in detail. As tree selection will depend, to some extent, on the establishment techniques being used, and vice versa, establishment techniques for trees are also discussed in this section.

3.1.1 Adaptation to the environment

Selection of trees that are adapted to growing in saline seeps presents particular difficulties. Hence selection for adaptation to saline seeps and non-seep areas are discussed separately.

SALINE SEEPS

In dryland agriculture, the term saline seep refers to an intermittent or continuous saline groundwater discharge, at or near the soil surface, that reduces or eliminates plant growth in the affected area due to the salt concentration in the root zone (Brown *et al.*, 1983). Generally saline seeps develop in valley bottoms, but occasionally they develop on hillslopes, for example above dykes or bedrock highs (Nulsen, 1985). The first sign of a developing saline seep in cleared land in south-west Australia is usually the prominence of the salt and waterlogging tolerant sea barley grass (*Hordeum marinum*) in the pasture. Core areas of well developed saline seeps, where depths to watertables are often (especially in winter and spring) less than 0.5 m, are mostly bare of even vegetation tolerant to salt and waterlogging.

It is often not possible, or not desirable, to reforest saline seeps with the trees that grew in those areas prior to clearing and saline seep development. As examples, many of the areas in the Wellington Dam catchment which are now saline seeps would have supported forests or woodlands dominated by the eucalypts *E. wandoo* or *E. rudis*. It is usually impossible to re-establish *E. wandoo* in saline seep areas because *E. wandoo* cannot tolerate the increased soil salinity and waterlogging conditions. *E. rudis* can be re-established in saline seep areas but frequently suffers extensive leaf loss due to leaf miner attack.

For successful reforestation of saline seeps, trees must be tolerant of the combined effects of high soil salinity and waterlogging (anaerobic) conditions caused by high watertables. Barrett-Lennard (1986) has pointed out the particularly important interaction between salinity and waterlogging in restricting plant growth.

Field trials have identified a number of salt/waterlogging tolerant tree species. With currently developed site preparation techniques (see section 3.1.4) it is generally possible to establish these trees in saline seeps except for the core areas of well developed saline seeps. Field trials have been reported from Western Australia (Hart, 1972; Biddiscombe *et al.*, 1981, 1985; Pepper and Craig, 1986; Ritson and Pettit, 1988), from Victoria (Morris, 1984) and from overseas (Donaldson *et al.*, 1983; Zohar, 1982; Mathur and Sharma, 1984). Although *Eucalyptus* species were the most common (or only) species planted in each of the above studies, the range of tree and shrub species covered by all trials also included species of *Casuarina, Acacia, Melaleuca, Atriplex, Tamarix, Leptospermum* and *Pinus*. There are apparent inconsistencies between studies in reported salt tolerances of species. This may be due to provenance variation within species. Also, differences between sites, not only in soil salinity, but in waterlogging and other site conditions, may have contributed to the apparent inconsistencies. Amongst the eucalypts, the species most consistently reported as salt tolerant were *E. occidentalis, E. sargentii, E. platypus* and *E. spathulata*. *E. camaldulensis* is a species commonly reported as being salt tolerant, although Pepper and Craig (1986) reported that the provenance of *E. camaldulensis* they planted at their Brookton site was not salt tolerant. *E. camaldulensis* is the most widely distributed eucalypt on the mainland of Australia and there are considerable differences in adaptability and performance between different provenances (FAO, 1979).

Recommendations of species for planting in sites subject to salinity and waterlogging have also been produced by Negus (1986) and the Woods and Forests Department of South Australia (undated). Besides the *Eucalyptus* species consistently reported as being salt tolerant, tree and shrub species recommended include *Casuarina obesa* and various species of *Melaleuca, Tamarix* and *Acacia.*

Further progress in plant selection is being made from studies in Western Australia supported by the National Biotechnology Program(Kabay *et al.*, 1986; van der Moezel and Bell, 1987; van der Moezel *et al.*, in press; and D. T. Bell pers. comm. 1988). An extensive range of species and provenances of *Eucalyptus, Casuarina, Melaleuca* and *Acacia* are being screened for tolerance to salinity and waterlogging stresses, both individually and in combination. So far the studies have mostly been in glasshouse conditions. Results confirm that there is a wide variation of tolerance between provenances of most species. This emphasizes the importance of selecting at provenance, rather than species level. Results from the glasshouse studies also show that selection of plants for tolerance to the single stress of salinity is a poor indication of tolerance to the combined stresses of waterlogging and salinity. Interestingly, tolerance to the single stress of waterlogging was found to be a much better indication of a plant's tolerance to combined waterlogging and salinity stresses. This emphasises the importance of selecting for waterlogging tolerance, as well as salinity tolerance when identifying plants for establishment in saline seeps. The identification, cloning and testing of superior individual plants is also being undertaken, but this work is at an early stage.

More research in plant selection for reforestation of saline seep areas is needed, particularly in selection for tolerance to severe salt-waterlogging stress conditions in core areas of saline seeps. It is only with a combination of improved plant selection and improved establishment techniques that it may be possible to establish tree or shrub cover in core areas of saline seeps.

NON-SEEP AREAS

Although some non-seep sites may present particular difficulties for tree establishment, e.g. sites with lateritic caprock, the environment is generally not as harsh for trees as it is in saline seeps. Therefore more trees are adapted to non-seep sites.

The task of identifying trees adapted to non-seep sites has been facilitated by the establishment of species selection trials. The large scale arboreta established in the Northern Jarrah Forest region have been particularly useful (Table 1). These were established as a result of a programme for systematic introduction and testing of species to replace jarrah (*E. marginata*) lost to bauxite mining, dieback and farm clearing (Bartle and Shea, 1978).

Table 1: Major arboreta in the Northern Jarrah Forest

Location	Site type	Year planted	Area (ha)	No. of species
Del Park	high rainfall minepit	1976	35	35
Marrinup	high rainfall dieback affected jarrah	1978	80	70
George upland	low rainfall jarrah upper topography	1979	80	70
George lowland	low rainfall jarrah low topography	1979	70	70
Stenes	low rainfall jarrah/ wandoo farmland	1979	80	65

Some species plots in the Stenes (Bingham River) Arboretum extend into a saline seep, otherwise the arboreta are in non-seep sites. The three arboreta in the low rainfall zone (George upland, George lowland and Stenes) are most relevant for identifying suitable trees for salinity control.

Bartle & Shea's (1978) approach to choosing species for testing was based on Havel's (1975b) observation that the competitive success of jarrah is apparently due to its ability to efficiently exploit water storage in the deep subsoil. They argued that replacement species for jarrah, being required to restore a similar water balance, would need to have similar slow growing, deep rooting and summer transpiration adaptations as found in jarrah. Given the many adverse features of the subsoil environment this was considered to be the major constraint on the success of introduced species.

The choice of species for testing was therefore biased to those from deep-soil, seasonally drought affected sites analagous to the jarrah environment. The two commercial *Pinus* species planted in south-west Western Australia, *P. radiata* and *P. pinaster* were included. Otherwise species selected were limited to the genus *Eucalyptus* which has numerous species from such sites. Eucalypts had the added benefits of ready availability of seed, adaptability to other factors such as fire and visual compatability with remaining natural forest. Some 70 eucalypt species were chosen and an average of two seedlots per species tested. There was a predominance of slower-growing species from the inland woodlands of Victoria, New South Wales and Western Australia.

Some fast growing forest species from the eastern States were included. Compared with the slow-growing woodland species these were generally from areas of higher rainfall with a more even annual rainfall distribution. Not many of these species were included due to the frequent observation from local plantings of drought death following rapid early growth (McArthur and Associates, 1985). Drought death was assumed to indicate inefficient soil water exploitation which would be reflected in poorer total water use. It was also seen to be a clear expression of poor adaptation, at least to the long-term, low management input regime considered appropriate for rehabilitation plantings of low commercial value.

The ecophysiological basis of the fast and slow growth patterns was explored by Hookey *et al.* (1987). In this study the patterns of leaf conductance and leaf water potential of the best performing species at age 5 to 6 years in the Stene's Arboretum were measured across the full seasonal drying cycle (spring to autumn). The results show the expected general decline in conductance over daily and seasonal cycles reflecting the systematic trends of increasing vapour pressure deficit and reducing soil water potential characteristic of the local environment. Since these two factors change in concert it is not possible to specify the conductance response to either one as being the dominant process in the regulation of water use (Schulze, 1986).

Within this general pattern of decline in conductance it was found that the fast and slow growing species tended to have two distinct seasonal patterns. The fast growing species (e.g. *E. viminalis, E. botryoides* and *E. saligna*) exhibited a high spring peak with a steep decline through summer. The slow growing species (e.g. *E. sideroxylon, E. microcarpa* and *E. polyanthemos*) had a flatter seasonal pattern, with moderate spring conductance which they were able to maintain over the summer drying cycle.

In an attempt to rank species for water use, crude estimates were derived from the conductance patterns. These were not convincing in terms of quantitative water use (see section 3.1.2) but gave qualitative support for conclusions on species adaptation and relative water use.

The slow growing species (*E. sideroxylon, E. microcarpa* and *E. polyanthemos*) all had good canopy cover (leaf area index from 2 to 2.5). Their ability to exhibit only moderate conductance in spring but to maintain it at moderate levels through the hot dry summer and autumn period, suggests a reliance on adaptations facilitating the exploitation of the deep soil profile e.g. deep root system, efficient extraction of soil water and tolerance of the harsh subsoil conditions such as acidity, salinity and high density.

The fast growing species (*E. viminalis, E. botryoides* and *E. saligna*) also had good canopy cover (leaf area index from 2 to 3.5). Their high spring conductance followed by a steep decline through summer suggests 'opportunist' adaptations to rapidly exploit easily available water and make rapid above-ground growth. This is probably a sound strategy in their native environment but in the 600 to 900 mm rainfall zone of the south west of Western Australia it exposes them to long periods in late summer with low conductance, and as the stand reaches full canopy cover, to water stress and risk of drought death. The widespread observation of rapid early growth and later drought death in fast growing species supports this conclusion.

Hookey *et al.* (1987) observed another indicator of stress in *E. saligna* when its leaf area index contracted from 2.5 to 1.5 during winter 1985. Further evidence of stress has been obtained from studies of stem volume growth over time using stem analysis. An 11 year-old stand of *E. globulus* on Stene's Farm (Figure 7) displayed good volume growth to age six, but in spite of a subsequent light thinning, its current volume increment levelled off before going into steep decline at age 10 (Figure 1). A more sudden arrest in growth, not moderated by thinning as in this case, is probably a feature of the drought death syndrome.

This sudden arrest of rapid growth probably also explains the relatively poor performance of *E. globulus* in the study by Hookey *et al.* (1987). In this study *E. globulus* did not display the characteristic fast growing conductance pattern. On one plot, located over shallow saline groundwater, the stand was especially poor with a leaf area index of 1.9 and low conductance. The second *E. globulus* plot over a deep unsaturated profile had grown much better (leaf area index 3) but conductance was low, probably indicating that the plot had already reached the stage of high water stress.

These results support the early assumption of poor adaptation to the environment in the fast growing species. However, the assumption that

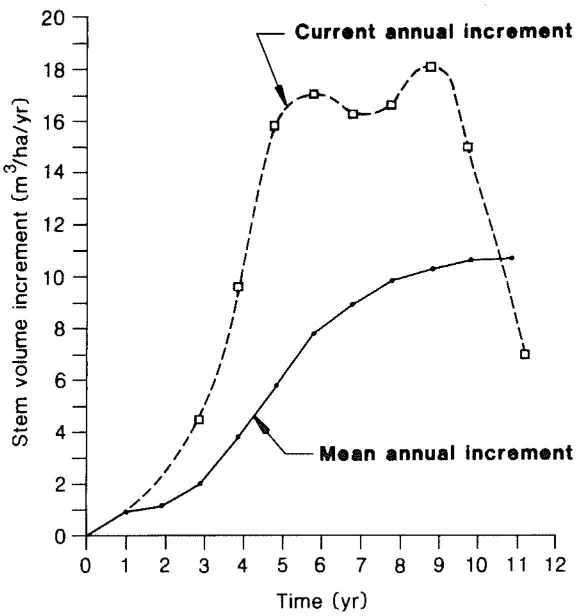


Figure 1: Mean and current stem volume increment for *E. globulus* on Stene's Farm, Wellington Dam catchment (volumes are means of 30 trees) (data provided by G. Inions pers. comm. 1989)

this was also linked to poor water use was not well supported. The high levels of conductance and large leaf areas indicate high water use during the fast early growth stage. The leaf water potential data in Figure 2 suggest that the fast growing species *E. saligna* may not extract soil water down to the same level of potential as the slow growing species. This would be important for the long term dewatering of substantial depths of unsaturated profile, or for the exploitation of saline ground water, but apparently does not greatly diminish total water use in the fast growing species during the early growth stage.

The contrasting growth habit of the fast and slow species opens the way to match them to appropriate site characteristics. The slow growing species would be most useful in a situation with a shallower or less permeable profile, especially if underlain by saline groundwater, due to their more conservative water use when water is readily available in spring and their ability to extract water at periodically lower potentials. The fast growing species could have a role on sites where soil water and groundwater of low salinity is available in an easily exploited profile. They could also form an early rapid growing, high water use component in species mixtures designed for long term sustained water use.

The Hookey *et al.* (1987) results led to a review of species used in the Wellington Dam catchment plantings. However, its most valuable contribution was in supporting a re-examination of the strategy of slow-growing, low management regime, non-commercial style of reforestation and developing a commercial alternative which would still be useful in salinity control. This is discussed further in section 3.1.3.

Another series of species trials on farmland in the Hotham River catchment was described by Biddiscombe *et al.* (1981 and 1985). There were four sites, two at Bannister (upslope and midslope locations) and one each at Dryandra and Popanyinning (both downslope locations). Long term average annual rainfall is approximately 800 mm at Bannister, 520 mm at Dryandra and 440 mm at Popanyinning. A total of 28 species (mostly *Eucalyptus* species) were planted at the four sites. At the Bannister (midslope), Dryandra and Popanyinning sites the plantations were placed across the upper edge of saline seeps so as to be partly on, and partly above, the seeps. The most useful plantation for assessing species adaptation to non-seep conditions is the Bannister (upslope) site where all the plantation of 13 species was located upslope of a saline seep. Ten species (*E. cladocalyx, E. melliodora, E. crebra, E. saligna, E. sargentii, E. maculata, E. patens, E. wandoo, E. robusta* and *Pinus canariensis*) showed good (>80%) survival in March 1977, 9 months after planting. At that time *E. globulus* had 69%

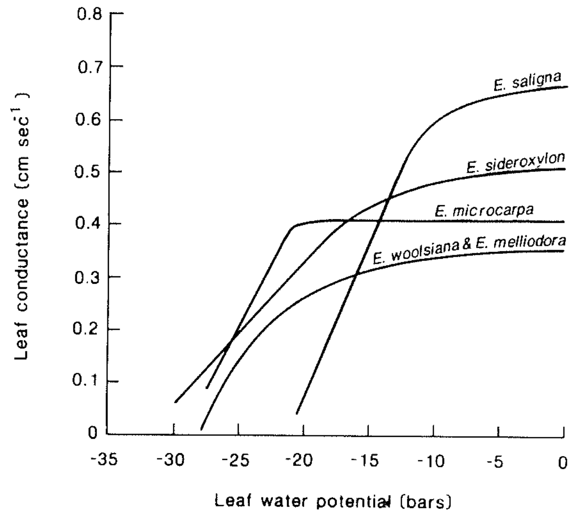


Figure 2:
Relationships between leaf conductance and leaf water potential for some species in Stene's Arboretum (from Hookey *et al.*, 1987)

survival, while *E. haemotoxylon* and *Tipuana tipu* had poor (<50%) survival. The species with good survival 9 months after planting maintained that survival rating to the last measurement in 1983 (age 7 years).

3.1.2 Tree selection on the basis of water use

INTRODUCTION

It is likely that different tree species, subspecies and even provenances transpire at different rates under identical conditions. It can be advantageous in a reforestation design to select trees on the basis of their water use performance. This section reviews recent studies conducted in south-west Western Australia and one study from Victoria on transpiration by trees.

VENTILATED CHAMBER STUDIES

Since 1976, Greenwood, in association with various co-workers, measured transpiration by pastures and several native and introduced tree species in south-west Western Australia using the ventilated chamber technique. All transpiration data quoted here from these studies are given as transpiration per unit ground area. The transpiration data obtained in these studies include evaporation of free water on leaf surfaces from intercepted rainfall or dew formation and evaporation of soil water. Measurements in these studies were usually taken several times per day on at least one day each month during the study period. All species to be compared were sampled on the same days. Linear interpolation between measurements was used to obtain a total transpiration for a measurement day and the study period. Throughout a study transpiration was always measured on the same individual trees.

In their earliest reported study, Greenwood and Beresford (1979) measured transpiration rates of a total of 13 *Eucalyptus* species at three different locations with long-term mean annual rainfalls of 850, 500 and 420 mm, respectively. Data were collected for two years in the months of November to April. These months represent a comparatively dry season in the south-west region during which only 20% of the annual rainfall occurs. During the wet season rainfall exceeds pan evaporation while during the dry season pan evaporation exceeds rainfall.

Greenwood and Beresford (1979) confined sampling to the dry season because they felt that this offered the best opportunity for differences in transpiration between species to be detected. However, unless trees have access to groundwater that is within a few metres of the soil surface and of relatively low salinity, their transpiration during the dry season is limited by the availability of water. The summer transpiration will thus depend on the amount of water transpired during winter and spring. Transpiration measurements from the dry season alone may not therefore correctly identify the tree species which can transpire the most over a year. The transpiration data collected in this study were also subject to variability in climate, landscape position, age (range 11–27 months) and depth to water table (range 2–8 metres).

Greenwood *et al.* (1981) compared transpiration from 16-year old *Pinus radiata* trees and an annual *Trifolium subterraneum*-based pasture in an agroforestry layout (Flynn's Farm—see Figure 7) where the two were interspersed. The long-term mean annual rainfall at this site is 900 mm. Transpiration was measured throughout a 14 month period during which 1030 mm of rainfall were recorded. Over this period the pasture transpired 90 mm and the trees 910 mm. The pasture only transpired from May, when it germinated, until November, when it died. During these same months, the trees transpired 460 mm of water. They transpired throughout the study period, but significantly more during the wet winter months (460 mm from May through October) than during the dry summer months (350 mm from November through April) even though pan evaporation is much higher in summer than in winter. The water table at this site was more than 20 m below the soil surface. Neutron moisture measurements showed there was no significant water extraction beyond a depth of 4.5 m.

Greenwood *et al.* (1982) compared transpiration from 15-year old *Eucalyptus wandoo* coppice regrowth with an adjacent annual *Trifolium subterraneum*-based pasture. The long-term mean annual rainfall at this site was 750 mm. Transpiration was measured over 11 months, during which 520 mm of rainfall were recorded. As in the agroforestry study, the pasture only transpired from germination in May until death in November. During this period the pasture transpired 450 mm which was equal to the amount of rainfall recorded. The trees transpired about 750 mm of water in the same period, and a total of 1100 mm over the full study period. Transpiration by the trees declined as the dry season progressed, which indicates that they were not able to utilise much, if any groundwater. The water table was 8 m to 10 m below the soil surface and significant amounts of roots were not found more than 3 m below the soil surface. Most of the water transpired in excess of the rainfall recorded during this study must therefore have originated from the unsaturated zone.

Transpiration was measured on five *E. wandoo* trees whose canopy areas differed. The transpiration values quoted above are an average for these five trees. The volume of water transpired by the individual trees on the days of measurement in the wet season was proportional to their canopy area. This was still true for the measurement in November. As time progressed, transpiration by the tree with the largest canopy area fell below that of the tree with the second largest canopy area, whose transpiration in turn fell below that of the tree with the third largest canopy area as the dry season progressed further (Figure 3). However, the total transpiration by the trees over a whole year was still proportional to their canopy area. This illustrates again that annual transpiration by trees cannot be correctly assessed from transpiration measurements in the dry season only.

The transpiration from several 6-year old *Eucalyptus* species and adjacent annual clover-based (*Trifolium subterraneum*) pastures was studied over one year by Greenwood *et al.* (1985) at a location with a long-term mean annual rainfall of 800 mm. During the study 684 mm of rainfall were recorded. Over this period pasture on the upper slopes of the site transpired 370 mm of water, and pasture on the middle slopes of the site transpired 410 mm of water. This corresponds to 54% and 60% of the rainfall recorded over the study period, respectively. As in the two previous studies, the pastures only transpired between germination in May and death in November. About 500 mm of rainfall were recorded over the same months. During these months, three tree species planted in a plantation on the upper slopes, namely *E. globulus, E. cladocalyx* and *E. maculata,* transpired some 1260, 1150 and 1000 mm of water, respectively. The total transpiration by these three species over the study period was 2690, 2660 and 2330 mm, respectively, which is equivalent to 3.4 to 3.9 times the rainfall recorded over the study period. *E. globulus, E. leucoxylon* and *E. wandoo,* which were planted mid-slope, transpired about 990, 950 and 780 mm of water, respectively, from May until November. Over the study period, they transpired 2210, 1840 and 1620 mm of water, respectively, equivalent to 2.4 to 3.2 times the recorded rainfall.

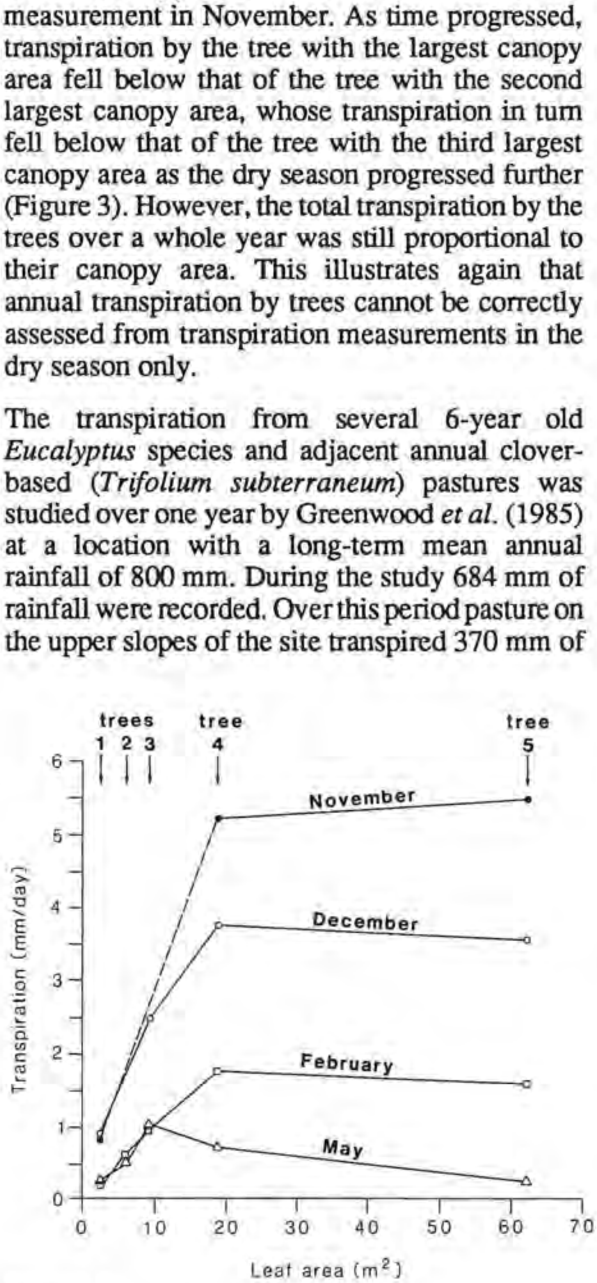


Figure 3:
Relationship between leaf area and transpiration for five wandoo trees at different times in the dry season (re-drawn from data of Greenwood *et al.*, 1982, with permission)

The water table varied from 2 m to 8 m below the soil surface in this study. Soil cores recovered from the area planted to *E. cladocalyx* showed that the roots of this species penetrated to 6 m below the soil surface, which is within the range of the water table. The rooting depths of the other tree species in this study were investigated at a later date and were also within the range of the water table (Greenwood, pers. comm., 1988). Utilisation of groundwater is the most likely reason why the trees in the study were able to transpire so much more water than the rainfall received, and why they generally transpired more during summer than during winter (Table 2).

Table 2: Annual and seasonal transpiration of the species at the upslope and midslope sites of Greenwood *et al.* (1985)

Site	Species	Transpiration (mm)		
		May-October	November-April	whole year
Upslope	*E. globulus*	1260	1430	2690
	E. cladocalyx	1150	1510	2660
	E. maculata	1000	1330	2330
	T. subterraneum	370	-	370
Midslope	*E. globulus*	990	1220	2210
	E. leucoxylon	950	890	1840
	E. wandoo	780	840	1620
	T. subterraneum	410	-	410

Transpiration of the *E. globulus* trees in the midslope plantation was 0.82 of those in the upslope plantation. The difference was due to the smaller canopy area of the midslope trees. Due to this difference, transpiration cannot be compared between trees planted upslope and midslope.

Transpiration by the species in the upslope and midslope plantations was also compared on a leaf area basis (Greenwood *et al.*, 1985). Presented in this way (Table 3), the ranking of species differs from that based on transpiration per ground area (Table 2).

Table 3: Annual and seasonal transpiration per unit leaf area of the species at the upslope and midslope sites of Greenwood *et al.* (1985)

Site	Species	Leaf area index	Transpiration per unit leaf area (m)		
			May-October	November-April	whole year
Upslope	*E. globulus*	4.3	293	333	626
	E. cladocalyx	3.2	359	472	831
	E. maculata	3.4	294	391	685
	T. subterraneum	0.9			
Midslope	*E. globulus*	3.4	291	359	650
	E. leucoxylon	1.3	731	685	1416
	E. wandoo	1.0	780	840	1620
	T. subterraneum	1.0	410	-	410

The studies discussed so far show that the tree species *P. radiata*, *E. globulus*, *E. cladocalyx*, *E. maculata*, *E. leucoxylon* and *E. wandoo* transpire substantially more over a year than the *Trifolium subterraneum*-based pasture. This is due to two factors. Firstly, the trees transpire throughout the year while the pasture transpires only during part of the year. Secondly, during the times when the pasture is transpiring, the trees transpire more than the pasture. The very low transpiration by pasture in the agroforestry layout of 90 mm (Greenwood *et al.*, 1981) compared to 370 mm to 520 mm in the other two studies (Greenwood *et al.*, 1982; Greenwood *et al.*, 1985), could have been due to shading of the pasture by the trees, competition for the water, or poor pasture establishment and growth.

Rooting depths in excess of 5 m can be expected from most tree species, while most pastures rarely exceed a rooting depth of 1 m. The roots of several eucalyptus species have been found at depths greater than 20 m (Campion, 1926; Dell *et al.*, 1983). Trees are therefore more likely to access groundwater. Their ability to transpire groundwater and potentially lower the water table in this way was alluded to by Greenwood *et al.* (1985). That reforestation can indeed lower the water table is demonstrated in sections 3.2 to 3.5. They can achieve this not only by transpiring groundwater, but also by reducing recharge to the point where groundwater outflow from the area planted exceeds recharge. A decline in the water table below a reforested area does therefore not necessarily imply that the trees transpired groundwater.

POROMETER STUDIES

Hookey *et al.* (1987) attempted a water use ranking on 23 eucalyptus species and provenances after 5–6 years of growth by measuring stomatal conductances with the porometer method. The site (Stene's Arboretum—Figure 7) had a long-term mean annual rainfall of 725 mm. The measurements were carried out from November 1984 into May 1985, and from mid-October 1985 into April 1986.

Conductance measurements were confined to the dry season because the authors felt that high transpiration in the dry season would clearly identify species which transpire the most groundwater. However, as highlighted by the ventilated chamber studies, high summer transpiration can indicate that a species has used less water in winter.

On average, conductances for a species or provenance were measured every ten days during the measurement periods. (In the remaining discussion of this study any reference to species shall include provenances). Measurements were taken three to six times per day. During each of the three to six daily samplings, conductances were measured either on 20 leaves at the top of the canopy or on 60 leaves throughout the canopy, depending on the species. The leaves were randomly selected within six strata (3 height x 2 aspect). No attempt was made to use the same leaves for each set of measurements. However, all measurements for a species were done on the same trees. Because of the large number of measurements taken only two to three species could be sampled per day. The combination of species measured on a given day was varied during the study.

For each of the three to six sets of daily measurements the conductances were averaged and then used in conjunction with the Penman-Monteith equation to compute daily transpiration from a leaf, expressed in mm of water per day per unit leaf area. The weather data required for the computation were collected at a climate station 7 km south-west of the study site. Total transpiration from a unit leaf area for various periods during the study as well as for the total study period from November 1984 to April 1986 was then obtained by interpolation. The interpolated transpiration values were summed for a specified period and the species ranked according to the total transpiration per unit of leaf area obtained for the period.

After considering the various rankings, Hookey *et al.* (1987) highlighted several species from the study which had moderate to high spring stomatal conductances and which maintained moderate levels of stomatal conductance into late summer. However, quantitative interpretation of their unit leaf area water use estimates are questionable for a number of reasons:

(a) measurements taken only during summer cannot accurately identify the annual transpiration by a tree;

(b) the ranking of some species was markedly affected by the interpolation method, although most were unaffected;

(c) the site conditions were not the same for each species—e.g. at planting the depth to the water table ranged from 5 m to 20 m, groundwater salinity ranged from 1 000 to 14 000 mg/L TSS, and some species were planted in discharge areas, others in recharge areas;

(d) measurements on the various species were not taken on the same day so that the results cannot be compared directly;

(e) the methods used to interpolate between measurement days have limitations.

In light of these problems the water use figures presented by Hookey *et al.* (1987) should be interpreted with caution. However the study did identify species which maintained relatively high leaf conductance under summer and autumn drought conditions, especially when in the presence of a shallow, saline water table.

Groundwater levels were monitored at Stene's Arboretum with a network of bores. Since reforestation the groundwater levels have declined under each of the planted tree species, though not by the same amount. The decline in groundwater level in the bores was closely related to the initial depth to groundwater (Figure 4). The plots for the various species were typically 80 m by 100 m wide and adjacent to each other. The analysis of

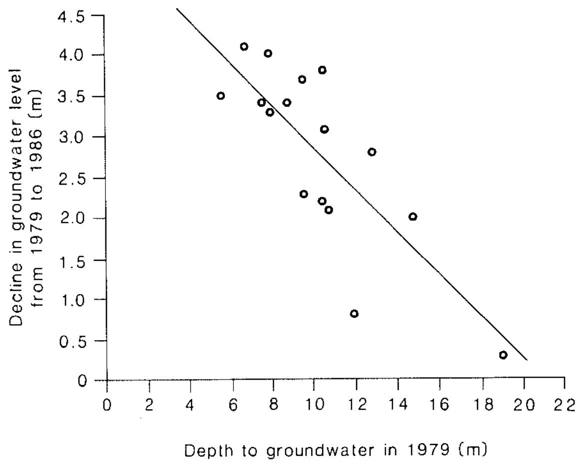


Figure 4: Relationship between depth to groundwater at planting and decline in groundwater level over the subsequent seven years at Stene's Arboretum

groundwater data indicates that the plots were too small and too close together for their underlying groundwaters to behave independently. Thus it is not possible to compare transpiration in this study from differences in groundwater level decline. The results do indicate, however, that the fastest rates of groundwater lowering following reforestation occur where trees can best access the water table.

In Victoria, Morris and Wehner (1987) determined transpiration by three year-old trees of *Eucalyptus camaldulensis, Eucalyptus grandis, Eucalyptus globulus* and *Eucalyptus botryoides* from porometer measurements. Measurements were carried out on nine days spread over an eleven month period. All species were sampled on the same day. On each sampling day measurements on *E. camaldulensis* were taken at several times throughout the day, but only at one time for the other three species. To account for within canopy variation of transpiration, the canopy of each species was divided into 24 separate zones. Transpiration per unit leaf area was measured directly with the porometer on several leaves in each canopy zone. Transpiration per unit ground area for each zone was then computed by multiplying the transpiration measured on leaves in the zone in question by the leaf area index in that zone. Finally, transpiration by a whole tree was obtained by summing the transpiration from each of the 24 zones. Daily and annual transpiration for *E. camaldulensis* was obtained by interpolation between measurement times. For the other three species it was determined by comparing the measured transpiration rates with those measured for *E. camaldulensis*.

Over one year, transpiration per tree was estimated to be 4350, 3760, 3620 and 1840 mm of water for *E. camaldulensis, E. globulus, E. grandis* and *E. botryoides*, respectively. In each canopy zone the highest transpiration per unit leaf area was observed in *E. camaldulensis*. Which of the other three species had the next highest value depended on the canopy zone in question. *E. globulus* and *E. grandis* partially compensated for the lower transpiration per unit leaf area by a greater leaf area. The low transpiration for *E. botryoides* was due to this species having stomata only on one side of its leaves, while the other three species have stomata on both sides. In all four species the leaves on the top and outside of the canopy transpired the most.

Morris and Wehner (1987) attributed the high transpiration values obtained in this study to a combination of the climatic conditions at the site, which are conducive to high transpiration rates, the constant availability of water due to irrigation, and the large canopy area of the species as reflected by the leaf area indices of 5.2, 7.0, 5.9 and 5.9 for *E. camaldulensis, E. globulus, E. grandis* and *E. botryoides* respectively. The trees were probably able to develop and maintain such high leaf area indices because irrigation prevented any serious water stress. During the study no water stress was observed except for some midday reduction of stomatal conductance on the most exposed leaves in the canopy on some hot, dry days.

The results from the study by Morris and Wehner (1987) are not of immediate relevance to the selection of trees for reforestation in south-west Western Australia. The exceptional leaf areas and minimal soil water limitation to transpiration are in striking contrast to local conditions. However, the study shows again that differences in transpiration are observed between species.

CONCLUSIONS

To date only a few studies on the transpiration of trees have been carried out. From the studies reviewed here the following conclusions can be drawn:

(1) The tree species *P. radiata, E. cladocalyx, E. globulus, E. leucoxylon, E. maculata* and *E. wandoo* annually transpire significantly more than *Trifolium subterraneum*-based pasture, as probably do most other tree species.

(2) There are differences in transpiration between tree species. However, transpiration by a species depends on site conditions such as mean annual rainfall and other climatic variables, landscape position, soil type, soil water salinity, groundwater salinity and depth to groundwater. Present data are insufficient to isolate species transpiration capacity from the 'noise' arising from particular site characteristics.

(3) The roots of trees penetrate to a greater depth than the roots of *Trifolium subterraneum*. Trees are therefore more likely to have access to groundwater. Several studies have shown that the water table is lowered below planted trees. They can achieve this by reducing recharge to the point where groundwater outflow from the area planted to trees exceeds recharge. They may also draw directly on groundwater.

(4) To obtain unambiguous results from studies on the transpiration by trees, all species to be compared should be of the same age, exposed to the same site conditions and sampled on the same days. Measurements should be carried out over at least one year and a method which accurately measures transpiration by a whole tree should be used. These requirements make reliable estimation of annual transpiration rates very difficult.

(5) Until better results of species ranking by annual water use become available, the adaptability of a species to the site in question and its other benefits, such as commercial or environmental values, should be the main considerations in its selection.

3.1.3 Wood production

Detailed observations of growth performance of the wide range of species used in operational plantings and field trials were undertaken during the mid 1980s.

A consultants report on the performance of all Wellington Dam catchment plantations established prior to 1982 was commissioned in 1985 (McArthur & Associates, 1985). Sample plots (mostly 10 m x 10 m) were selected to represent the range of species, plantation ages, topographic positions and soil types in plantation areas. The minimum sampling intensity aimed at was one plot per five hectares. Growth characteristics of all trees in the plots were assessed. A qualitative summary of performance and potential for ongoing use was presented for each species.

The study revealed good growth performance in the forest species *E. globulus* and *E. saligna* but also noted a 'sudden block death' problem for these species. It suggested that better matching of these species to the higher guality sites (i.e. mid-slope, freely-draining) would reduce the problem. The commercial pine species, *P. radiata* and *P. pinaster,* also showed good growth. The local species, *E. marginata, E. calophylla* and *E. wandoo,* suffered mortality. This was apparently partly due to grazing by stock which were prematurely reintroduced to the planted areas. This problem was exacerbated by the inherent slow growth of these species.

Comparison of height growth of species in the trial plantings in the Hotham River catchment at age seven years was reported by Biddiscombe *et al.* (1985). At the Bannister upslope site the fastest growing species were *E. globulus* and *E. saligna* followed by *E. cladocalyx* and *E. maculata.* At the other sites, where the plantations were established across the upper edge of saline seeps, the fastest growing species were *E. globulus* and *E. saligna* at the Bannister midslope site, *E. occidentalis* and *E. sargentii* at the Dryandra site and *E. cladocalyx* and *E. occidentalis* at the Popanyinning site. No measures of stem diameter were made although estimates of leaf area and crown volume were taken. Ranking of species at each site for these parameters was similar to that for height.

A comprehensive evaluation of growth performance in the Northern Jarrah Forest arboreta (Table 1) was undertaken in 1984–85 (Davey and Bartle, unpublished report). A 10% sample of trees was assessed for survival, height, diameter, form, vigour and defect. A method was developed by which the measured parameters could be integrated to produce a rating for each tree expressed as a percentage of the best tree in all plots. Plot means and 95% confidence intervals were calculated for all parameters including rating.

Growth performance at the Stene's (Bingham River) Arboretum generally exceeded the others, probably due to the greater fertility of this ex-farmland site. This site is also the most representative of land required to be reforested to improve catchment water quality.

Table 4 provides data from Stene's Arboretum contrasting the performances of some fast growing forest species with those of some slow growing woodland species. The fast growers produce more than double the wood volume at age six years and had the advantage of better form, making them easier to harvest. The fast growing species were also the best performers at the other arboreta.

A comprehensive search for and analysis of plots of *P. radiata* throughout the Albany region was undertaken by Ellis (in prep.). Using stem analysis, height/age and volume/age relationships were constructed for a range of sites. Timber volume production, even down to 700 mm rainfall, turned out to be surprisingly good. Also, in the moderate south coast environment, *P. radiata* is not prone to drought death as it is further north. The study showed that commercially attractive yields could be obtained, and this was the basis for the initiation of pine sharefarming operations in the Albany region.

Table 4: Stene's Arboretum: growth of best plot to age six years (after Davey and Bartle, unpublished)

Species	Survival %	Height (m)	Diameter (cm)	Form	Rating %
E. globulus	83	10.9	14.5	2.4	59
E. botryoides	85	11.2	14.6	2.7	60
E. viminalis	69	14.8	16.3	2.0	64
E. camaldulensis	88	9.5	12.1	0.8	38
E. microcarpa	97	7.7	9.2	0.2	34
E. sideroxylon	57	9.5	16.7	0.3	49
E. polyanthemos	98	7.7	11.8	0.4	40

Given the promise of reasonable yields and water use by fast growing species, and the possible development of a pulpwood sharefarming industry, a search for and analysis of performance of all possible stands of *E. globulus* were initiated late in 1987.

A standard operational planting of *E. globulus* on the ex-Malcolm property in the east Wellington catchment (650 mm/yr average rainfall) was at an appropriate age and size for harvest for pulpwood. Detailed stem analysis and coppice management trials were undertaken. This stand provides valuable insight into how *E. globulus* should be managed at a rainfall considered to be at the lower extremity for its commercial use. The stand occupied a 70 m by 450 m strip of typical mid-slope sandy loam lateritic gravel soils. A surface soil assessment would probably have rated the site as high quality and suitable for planting to the drought-prone *E. globulus,* though the occurrence of a single remnant wandoo tree suggested declining suitability towards one end of the plot. The harvestable volume along the length of the plot ranged from 150 m^3/ha to 90 m^3/ha at age eight years (i.e. mean annual increments (MAI) of 19 m^3 to 11 m^3). This decline from what is an attractive commercial yield down to a poor yield indicates the importance of site selection. It will be essential to develop site assessment procedures which can resolve these commercially important differences. Stem analyses of 43 stems indicated that maximum MAI was achieved at age eight years (Jenkin, 1988). Early drought death had occurred at the poor yielding end of the plot. These observations also strongly support the standard spacing adopted (4 m x 3 m) since a suitable size stem (15 m high and 20 cm diameter at breast height) was produced at age eight years.

Inions (pers. comm. 1988) has identified a further 60 plots of *E. globulus* which provide useful growth data. These plots cover the full climatic and geographic range over which short-rotation eucalypt crops may be grown. Stem analysis was undertaken at each site. The data from this study provides the basis for estimation of management costs and yield for the pulpwood cropping industry now being set up.

3.1.4 Establishment techniques

NON-SEEP SITES

In some situations good regeneration occurs around remnant native trees (especially *E. rudis*) when stock are excluded. This has never been developed as an operational practice because of the uncertainty of success.

Reforestation may also be achieved by direct seeding or the planting of seedlings or vegetatively propagated plants. Direct seeding may be the cheaper method, but planting is generally more reliable. In the Wellington Dam catchment project some initial attempts at direct seeding on a trial basis were unsuccessful. All operational scale reforestation there has been from planted seedlings. Whether reforestation is by direct seeding or planting, site preparation is essential.

The site preparation of non-seep areas involves the following procedure. Sites are ripped in late summer/autumn when soils are driest so maximum breaking up of soils is obtained. A tractor and single tyne chisel ripper is used to rip to 20–30 cm depth. The ripping is done along planting lines four metres apart and on the contour. Ripping along, rather than across the contour, increases soil moisture retention and reduces erosion. Although this may have the undesirable effect of increasing groundwater recharge initially, it is necessary to provide adequate moisture for seedlings especially during the critical first summer after planting.

After pasture germination (around May) a 1.5 m strip along each rip line is sprayed with herbicide for pasture control. This is necessary to reduce moisture competition with planted seedlings. Tractors and boom sprays are used. Vorox AA is usually the herbicide applied. It contains post-emergent (amitrole) and pre-emergent (atrazine) ingredients to give rapid knock down and residual control of pastures for one growing season. Containerised (small peat pot) seedlings are hand planted in June or July. They are placed in a hole made with a wedge shaped planting spear and the soil firmed around each seedling by the planter's boot. The current practice is to fertilise all seedlings, either at planting time or within one month of planting. One 30 g pellet of DAP (18% N, 20% P) fertiliser is placed in a planting spear hole 10–15 cm downslope of seedlings.

SALINE SEEPS

As with non-seep areas, site preparation for reforestation of saline seeps should include ripping, pasture control and, if warranted, fertilisation. However, ripping should be across, rather than along the contour to minimise soil moisture retention which would add to waterlogging problems.

Ridge mounding is an additional site preparation technique for waterlogged soils used to improve tree establishment and growth (Langdon, 1962; Yadav, 1980; and Geary *et al.*, 1983). By planting seedlings in the tops or sides of mounds they are raised above the water table. Furrows are usually created to obtain soil for the mounds. By aligning the mounds and furrows to provide drainage, further reductions in waterlogging of seedlings are obtained. In field operations to date, ridge mounds have been formed over rip lines with a tractor and mound plough. The plough has offset discs designed to heap soils into a ridge mound between the discs. When first formed the mounds are approximately 15–20 cm high and the furrows formed by each disc are approximately 10–15 cm deep. With these mounds it has been possible to establish salt-waterlogging tolerant eucalypts in saline seeps except for core areas of well developed saline seeps.

Recognition of the problems of reforestation of core areas of well-developed saline seeps led to the commencement of a research programme in 1986 to improve reforestation techniques. Background to the research programme and some initial results are described by Ritson and Pettit (1988) and summarised here.

(a) Background

Alternative strategies for research to improve reforestation of difficult sites are:

(i) Plant selection trials—to find suitable plants which are most tolerant of the environmental stresses.

(ii) Establishment trials—to find ways of reducing environmental stresses by modifying the environment or changing planting practices.

Most progress in improving reforestation of saline seeps is likely to come from a combination of the two research strategies.

In contrast to plant selection research (discussed in sections 2.3 and 3.1.1) there appears to have been very little research to improve establishment techniques. Hence a comprehensive set of establishment trials was commenced. Although these trials are in the Wellington Dam catchment, other water resource catchments in Western Australia have similar sites and a similar salinity problem. Thus the results should have application for assessing the potential for reforestation in those catchments and implementing any reforestation projects.

(b) The trials

Establishment trials initiated to date, with the question they were designed to answer, are listed below. All the trials were set out in the field as randomised block design experiments with at least two species in each trial and row plots of 12–15 seedlings. Evaluation of treatments will be based on survival and growth rates of seedlings.

(i) Mounding: What is the best size and shape of ridge mound to plant seedlings in?

(ii) Drainage: Can the furrows formed to construct ridge mounds be effectively used as parallel open ditch drains to provide site drainage?

(iii) Mulching: Can mulches be used to reduce salt accumulation in ridge mounds?

(iv) Deep ripping: Will ripping of hardpan sites to 1.6 metres depth allow tree establishment?

(v) Seedling containers: Will bigger containers, or those which allow chemical root pruning, give more robust seedlings?

(vi) Planting time: Can this be altered to take advantage of seasonal changes in salinity and waterlogging conditions?

(vii) Fertiliser: What is the best fertiliser regime (if any) for seedlings?

The blocks (replicates) in each trial were located to cover a range of salt-waterlogging stress conditions, but so that within block variation in salt-waterlogging stress and other environmental conditions was minimised. Trials (i)–(iv) had blocks only in saline seeps. Trials (v)–(vii) had blocks in saline seep and non-seep sites.

The only establishment trials which have progressed sufficiently to allow conclusions to be drawn are the mounding trials. Hence they are the only results presented here.

(c) Results of mounding trials

Two trials, commenced in 1985 and 1986, with one metre high mounds formed in core areas of well developed saline seeps indicate that, with this drastic site preparation, it is possible to establish trees in these sites (Ritson and Pettit 1988).

However, other research indicates it may not be necessary to make the mounds quite so high if the design is changed.

Malcolm and Allen (1981) and Malcolm (1983) describe an alternative mound design for seeding salt bushes (*Atriplex* spp) in saline soils subject to occasional waterlogging. Instead of the standard single ridge mound used for tree establishment they used a double ridge mound and established salt bushes in the trough (niche) between the ridges.

A trial was commenced in July 1987 to test the double ridge mound design for tree establishment. Treatments included single and double ridge mounds of four heights formed with a road grader (mound heights 0.25, 0.5, 0.75 and 1.0 m) as well as standard mounds formed with a mound plough. Seedlings were planted in the tops of standard mounds, in the sides of single ridge mounds (at 0.75 of mound height) and in the trough bottoms of double ridge mounds (Figure 5). Heights of trough bottoms in the double ridge mounds, in order of increasing mound height, were approximately 0.1, 0.3, 0.5 and 0.75 m.

As shown in Figure 6 the results have been very encouraging. Trends were the same for both species. Clearly the double ridge mounds gave better establishment (survival rates) than the single ridge mounds. Establishment in standard mounds was better than in the single ridge mounds up to 0.5 m high. This may have been due to the small trough in the standard mounds which is formed by the roller packer pulled behind the mound plough. Only comparatively small improvements in establishment were obtained with increasing mound height.

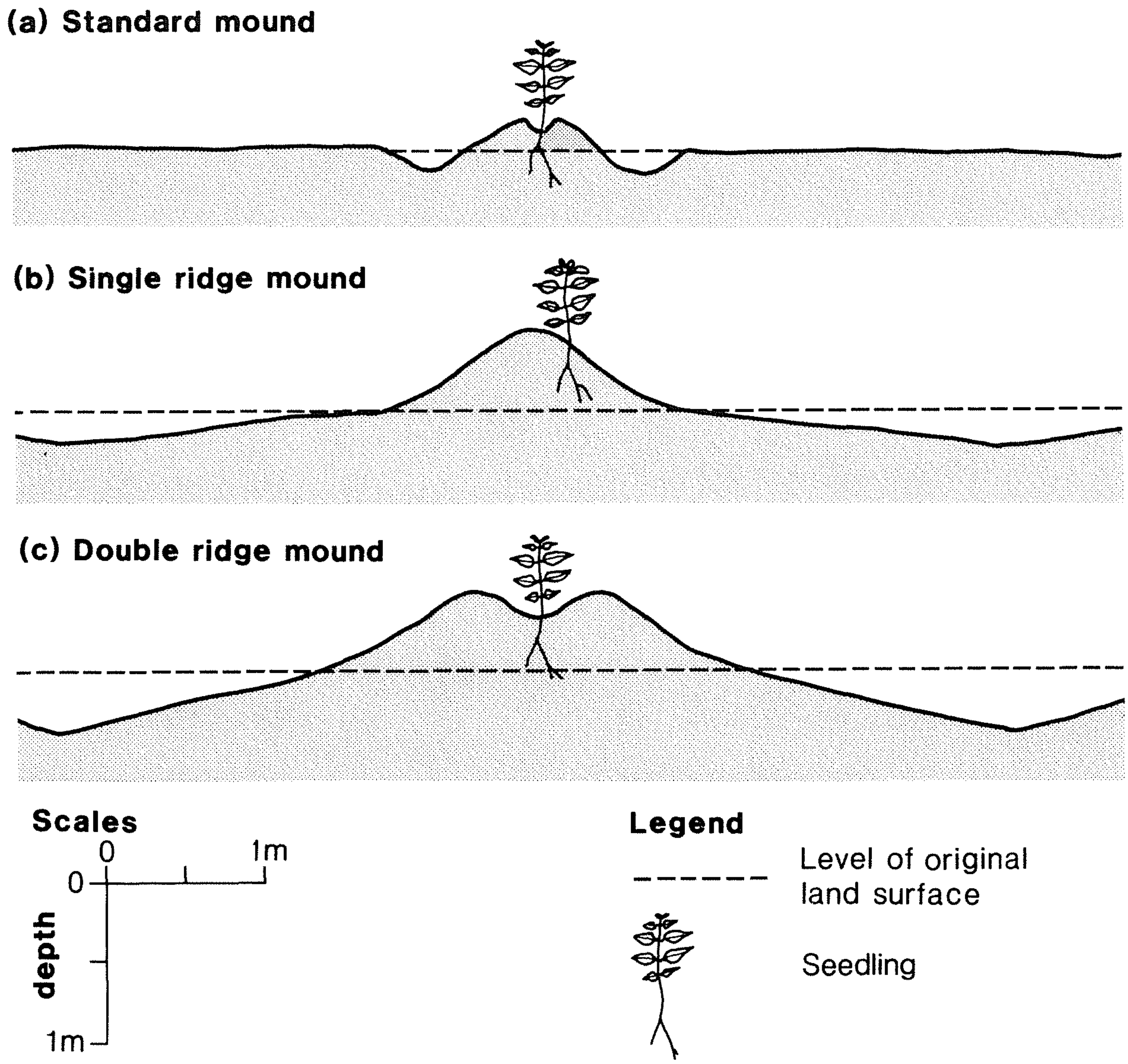
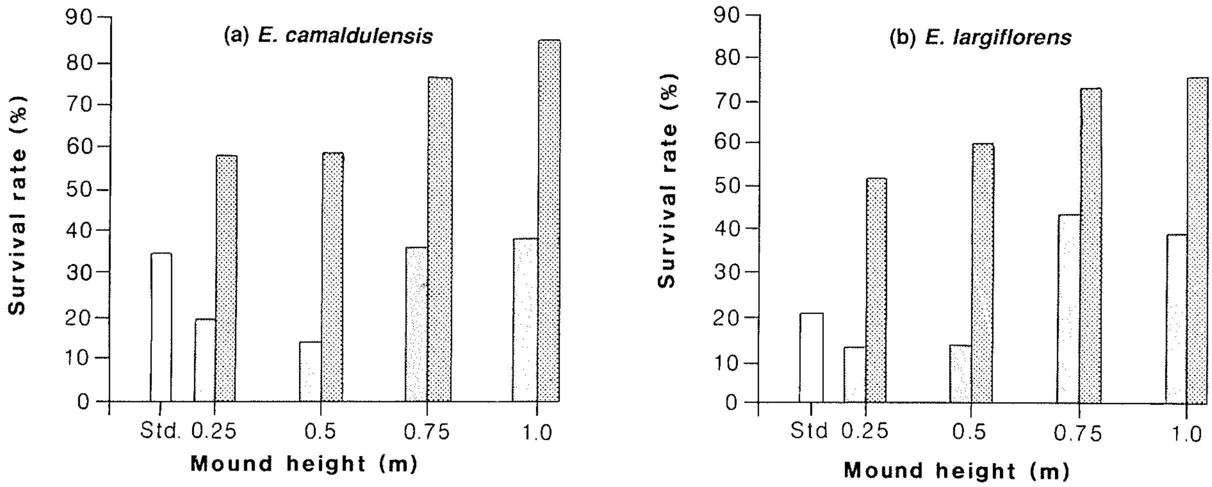


Figure 5: Cross-sections of a standard mound and 0.5 m high single and double ridge mounds showing positioning of seedlings

One essential difference between the single ridge and double ridge mounds appears to be the effect on soil salinity in the seedling root zones. Single ridge mounds would tend to shed rainfall and wet up either from the water table below or from water collected in the furrows formed to make the mounds. This would cause salts to accumulate in single ridge mounds. Such an effect has been demonstrated in laboratory studies (Bernstein and Fireman, 1957) and reported from field studies (Bernstein *et al.*, 1955 and Fanning and Carter, 1963). In contrast to the single ridge mound, the double ridge mound would tend to collect, not shed, rainwater because of the trough. This would facilitate rainfall percolation and therefore salt leaching from soil in the seedling root zone. Some waterlogging may also occur especially in winter. However this is likely to be temporary due to the free draining nature of the mounds. Also reducing salinity would reduce the impact of the salinity - waterlogging interaction. In summer when drought, not waterlogging, is likely to be the problem the effect of the trough in double ridge mounds in catching water from occasional rainfall events and channelling it to seedling root zones would benefit the seedlings.

The actual patterns of salt and water movement in the single and double ridge mounds in the trial are being monitored by soil sampling and analysis.

The use of double ridge mounds appears to be a promising technique to improve tree establishment in saline seeps. However more research is needed to determine the best design for double ridge mounds. In particular trough width may be important. A wider trough would catch and



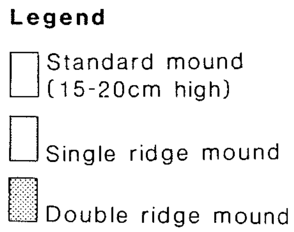


Figure 6: Mounding trial—survival of *E. camaldulensis* and *E. largiflorens* at age four months

channel more water to the seedling root zone. However an excessively wide trough may catch too much water, causing excessive waterlogging, and would be expensive to construct. A trial specifically to investigate the effect of varying trough width on tree establishment commenced in July 1988.

3.2 Lower Slope and Discharge Zone Planting

3.2.1 Rationale

To date in Western Australia, the principal method of attempting to restore salinised streams to potable levels has been tree planting on lower slopes and discharge areas (see section 4.2 for description of the Wellington Dam catchment reforestation programme). This approach was taken principally because it was seen as the only method by which partial reforestation could eliminate solute discharge to streams by groundwater. Clearing of native forest in valley floors had led to significant stream salinity increases, even though the area cleared was a small proportion of the total catchment (see Steering Committee for Research in Land Use and Water Supply, 1988, Figure 13). It was further argued (Loh, 1985) that lower slope and discharge area plantings would have a much quicker effect on reducing stream salinity. Reforestation of the lower landscape would also allow agriculture to continue upslope of the plantings.

Against these arguments it was realised that tree planting in saline and seasonally waterlogged discharge areas would be a difficult task. Some of these areas occupy significant proportions of the landscape (10–25%) and would cover as much as 50% of the area to be replanted. Another argument against this approach was that groundwater solute concentration would increase beneath the plantations over time to the extent that the survival of the plantations would be in question. Despite these doubts large-scale catchment rehabilitation was commenced on the Wellington Dam catchment in 1979 with lower slope and discharge area plantings. It was argued that agricultural strategies should be developed to minimise groundwater recharge on the cleared areas upslope of the plantations. This, it was suggested, would alleviate the problem of increasing groundwater salinity beneath the lower slope plantations.

At the outset of the reforestation programme it was appreciated that considerable research and evaluation was required to tackle the essential problems of tree selection, establishment and growth performance; areas and layouts of plantations; and determination of the ability of plantations to lower groundwater tables and stream salinities over a range of site conditions. Tree selection and establishment have been discussed in section 3.1. Areas and layouts of reforestation are considered in section 4.1. The responses of

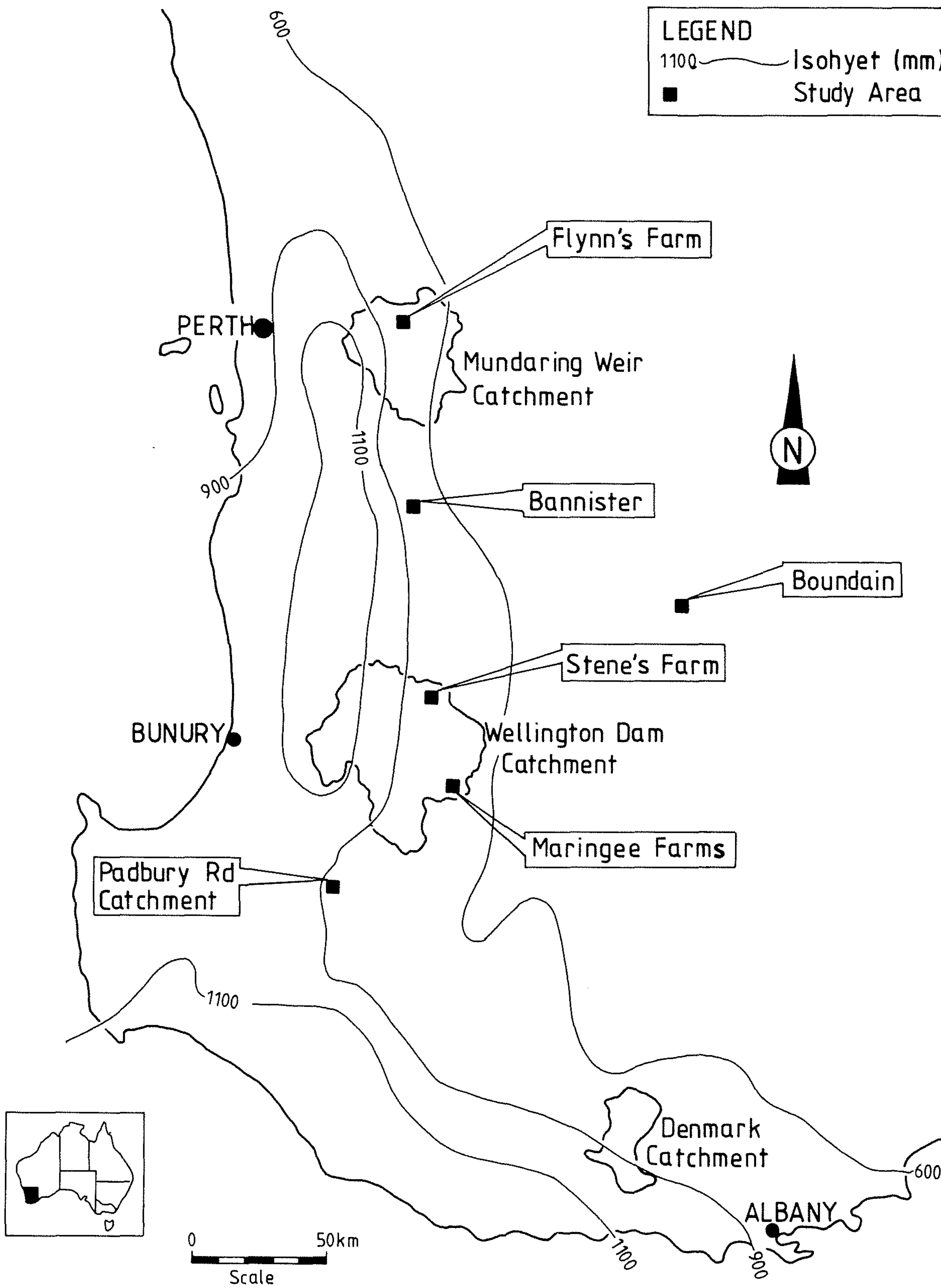


Figure 7: Location of study areas

groundwater levels and salinity to lower slope and discharge zone planting are discussed in the following section. Further details of the groundwater responses at Flynn's, Stene's and Maringee Farms are given by Bell *et al.*, (1988).

3.2.2 Groundwater responses to lower slope and discharge zone planting

Groundwater level and salinity have been monitored at two sites with lower slope and discharge area plantings. The sites are located on Stene's

Table 5: Characteristics of lower slope and discharge zone planting sites

Site	Annual rainfall (mm)	Planting year	Species planted	Initial planting density (stems/ha)	Stem density in 1986 (stems/ha)	Percent of site cleared (%)	Percent of cleared area replanted	Crown cover at 1987 (%)	Initial depth to water table (m)		Initial average salinity (mg/L TSS)	
									Mean	Range	Mean	Range
Stene's Valley Plantings	725	1979	*E. wandoo* *E. rudis* *E. camaldulensis*	625	500	44	35	41	6.3	1.9 to 13.3	5400	3000 to 9600
Maringee Farms	650	1981/2	*E. camuldulensis* *E. wandoo* *E. saligna*	625	250	54	22	?	2.2	0 to 4.6	15600	370 to 22800

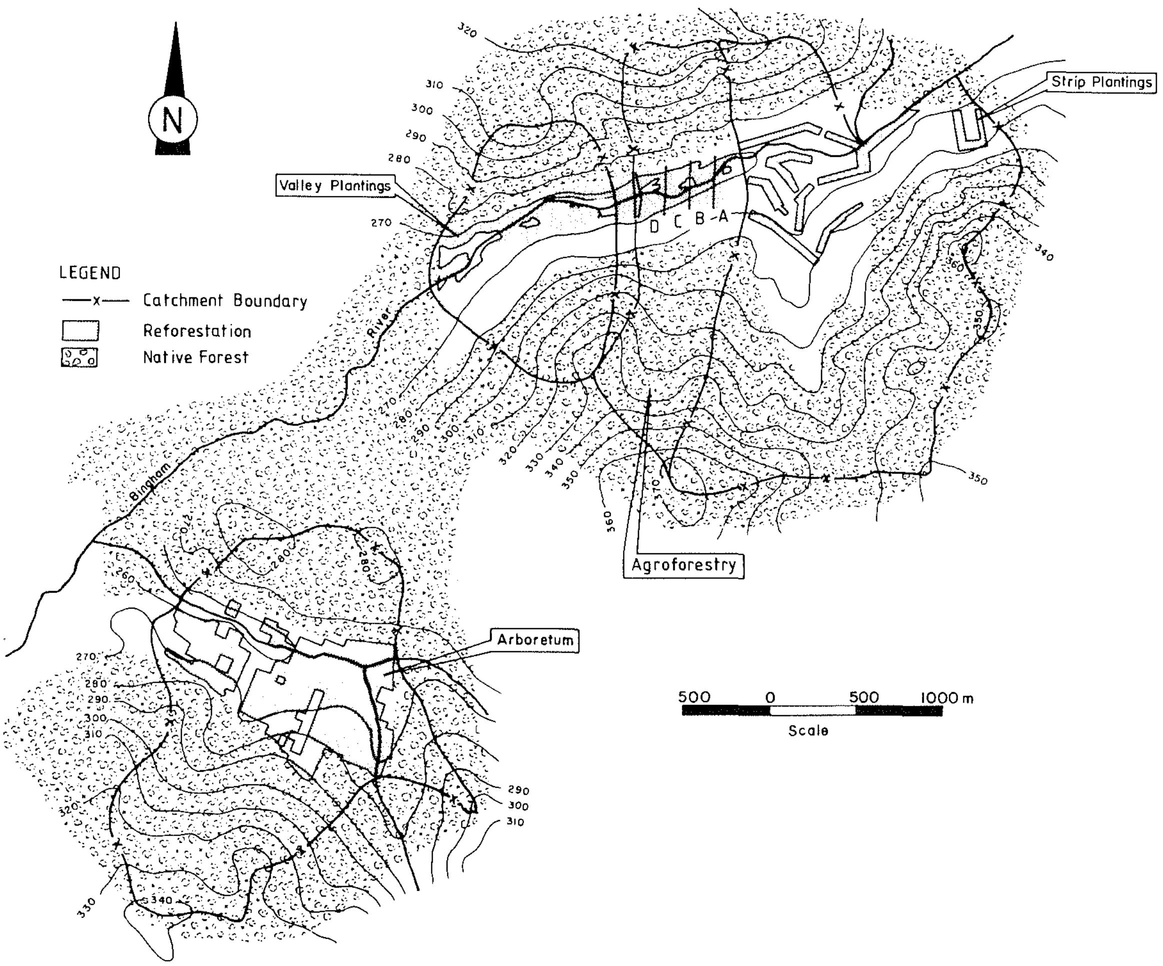


Figure 8: Stene's Farm experimental reforestation sites

Farm and Maringee Farms, in Wellington Dam catchment (Figure 7). The characteristics of these sites are given in Table 5. The site characteristics and groundwater responses are discussed individually below.

Stene's Valley Plantings

The Valley Plantings site was developed for agriculture in the 1950s along the streamline and lower slopes (Figure 8). Forty-four percent of the experimental catchment area was cleared. In 1979 *E. wandoo, E. rudis* and *E. camaldulensis* were planted north of the Collie-Williams road at a density of 625 stems/ha, covering 35% of the cleared area. A transect of bores across the valley was also established in 1979. The transect passed from native forest through the pastured area and reforested area back into native forest. The initial average minimum depth to groundwater in the cleared area just prior to replanting was 6.3 m and the average groundwater salinity was 5400 mg/L TSS. While there was evidence of a saline seep upstream of the bore transect, on the bore transect itself there were no saline seeps evident.

The response of the annual minimum groundwater level under reforestation is shown in Figure 9. In the first four years (1979–82) there was a net increase in groundwater level of 0.5 m, but from 1982–86 there was a steady decline. Over the total period (1979–86) there was a net reduction in minimum groundwater level of 0.8 m. In contrast the groundwater level under pasture rose by

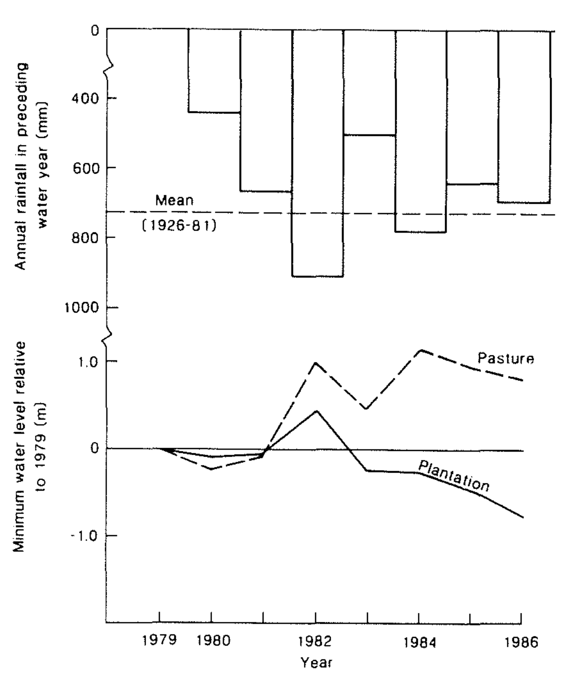


Figure 9: Annual rainfall and groundwater level variations at Stene's Valley Plantings site

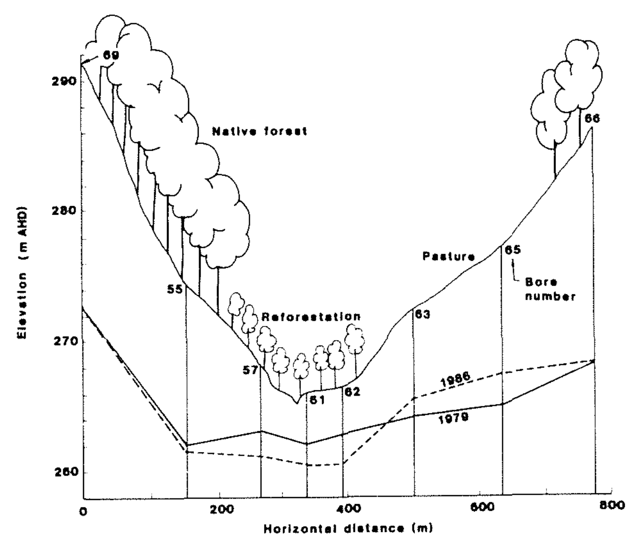


Figure 10: Comparison of valley cross-section potentiometric surfaces of 1979 and 1986 at Stene's Valley Plantings site

0.8 m over the 1979–86 period. Groundwater levels under both reforestation and pasture were strongly affected by annual rainfall, with the annual groundwater minima responding to rainfall of the previous water year (1 April–31 March). This is exemplified by the peak in groundwater minima which occurred in 1982 for both reforested and pasture areas following the well-above-average rainfall of the previous year. This was followed by a significant drop in groundwater minima the next year, which followed a year of well-below-average rainfall.

A comparison between the groundwater potentiometric surface across a valley cross-section between 1979 and 1986 is shown in Figure 10. There is seen to have been little change under native forest, a net reduction under the reforested area and a net increase under pasture. This is a good example of the localised impact of vegetation type on groundwater behaviour.

Maringee Farms

Maringee Farms is the most eastern of the water resource catchment experimental sites and exhibits the most severe conditions of salinity-waterlogging in which operational scale reforestation has been attempted. The experimental catchment area was 54% cleared prior to reforestation. In 1981/82 about 22% of the cleared area was replanted with a range of species but principally *E. camaldulensis, E. wandoo* and *E. saligna* at a stem density of 625 stems/ha (Figure 11). In the early stages of growth the plantations suffered some stock damage (I. Loh pers. comm., 1988). However the site also has a very high groundwater

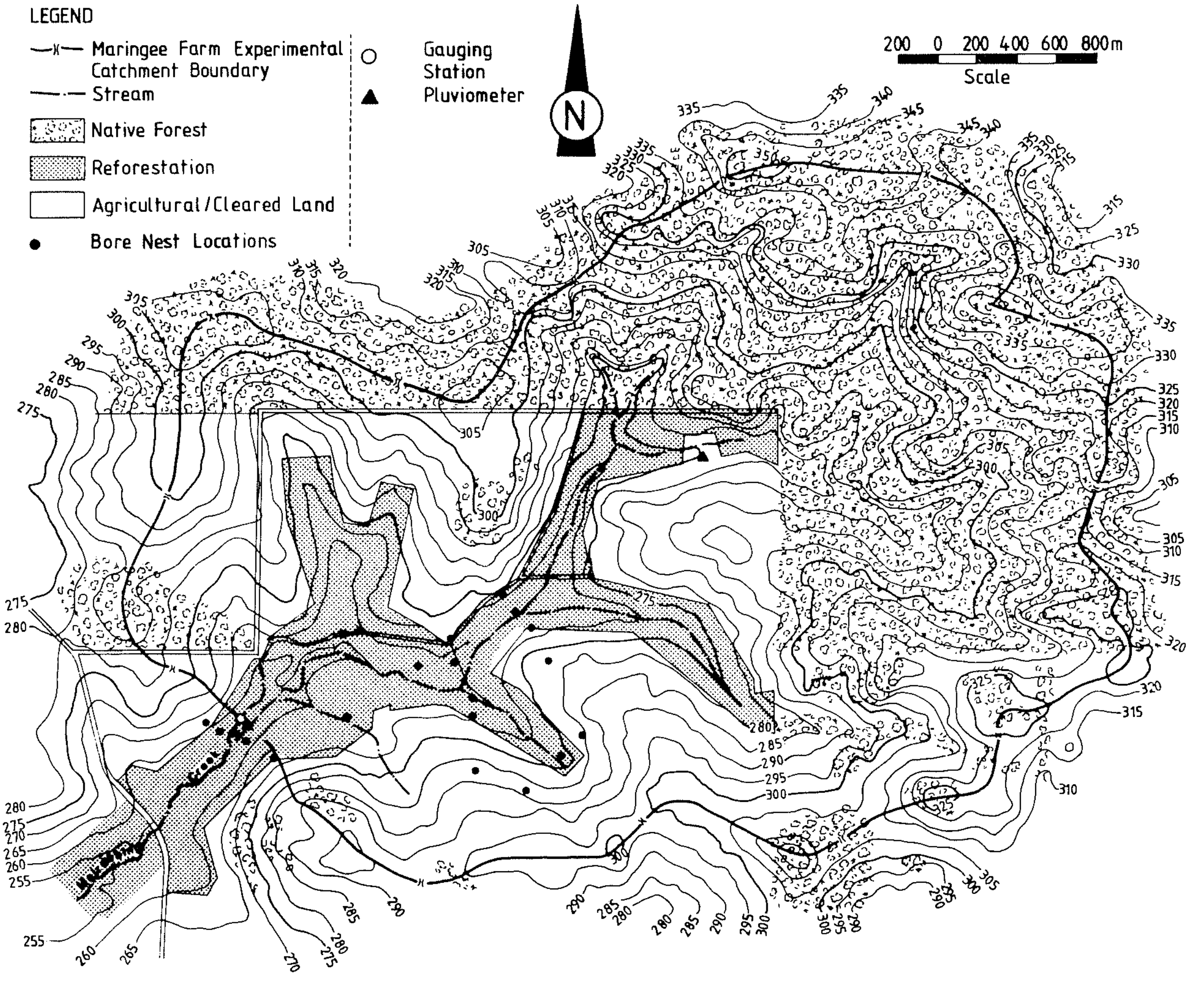


Figure 11: Maringee Farms study site

salinity (initially 15 600 mg/L TSS under the reforestation area) and shallow watertable (average minimum value of 1.1 m under the reforestation). The seep area itself was estimated to cover about 13% of the experimental catchment. These conditions together with stock damage have resulted in poor survival rates. By 1986 the stem density had reduced to about 250 stems/ha.

In 1981 a number of individual bores and bore transects were established in the catchment (Figure 11). Details of the hydrogeology and initial groundwater flow patterns are given by Martin (1984). One significant characteristic of the groundwater system at this site is the strong upward pressure gradient in the valley. This is considered to be due to the extensive clearing to the ridge lines.

Figure 12 shows the response of groundwaters under the pastured and reforested areas. Between 1982 and 1986, the groundwater level in the upslope pasture bores rose by about 2.0 m. Under the valley reforestation there was a 0.25 m reduction in groundwater level. However it should be noted that the years 1984–86, and in particular 1986, had well-below-average annual rainfall and the observed reduction in the groundwater level may not be maintained under normal rainfall conditions.

The response of the groundwater potentiometric surface across one transect of the catchment is illustrated in Figure 13. It is clear that all of the water level reduction has occurred on the northern (left hand) side of the valley where the proportion of area replanted is about 35%. On the other side of the valley only 15% of the hillslope was replanted and there has been no reduction in

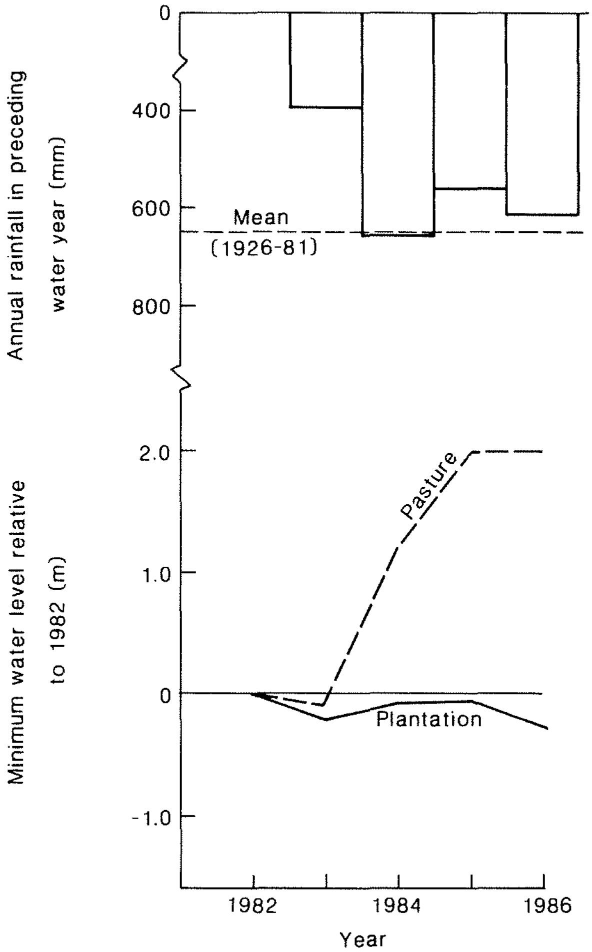


Figure 12: Annual rainfall and groundwater level variations at Maringee Farms

groundwater level under the plantation. Under the pasture upslope there has been a significant increase in the water table level.

Despite the poor survival of trees at Maringee Farms, the depression of water table where adequate plantings exist gives some hope for rehabilitation under these severe environmental conditions.

3.3 Wide-Spaced Plantations (Agroforestry)

3.3.1 Timber aspects of wide-spaced plantations

The combination of wide-spaced pine for sawlogs and pasture for grazing (agroforestry) has been extensively researched in Western Australia. The first trials were established in 1973 and methods of management have been developed and levels of timber and agricultural production determined (Anderson and Moore, 1987). Tree arrangement and density, culling and pruning practices and farming amongst pines have been evaluated and firm guidelines provided (Dept. Conservation and Land Management, 1987). Some more recent developments in this area were mentioned by Moore (1988). An economic study of agroforestry

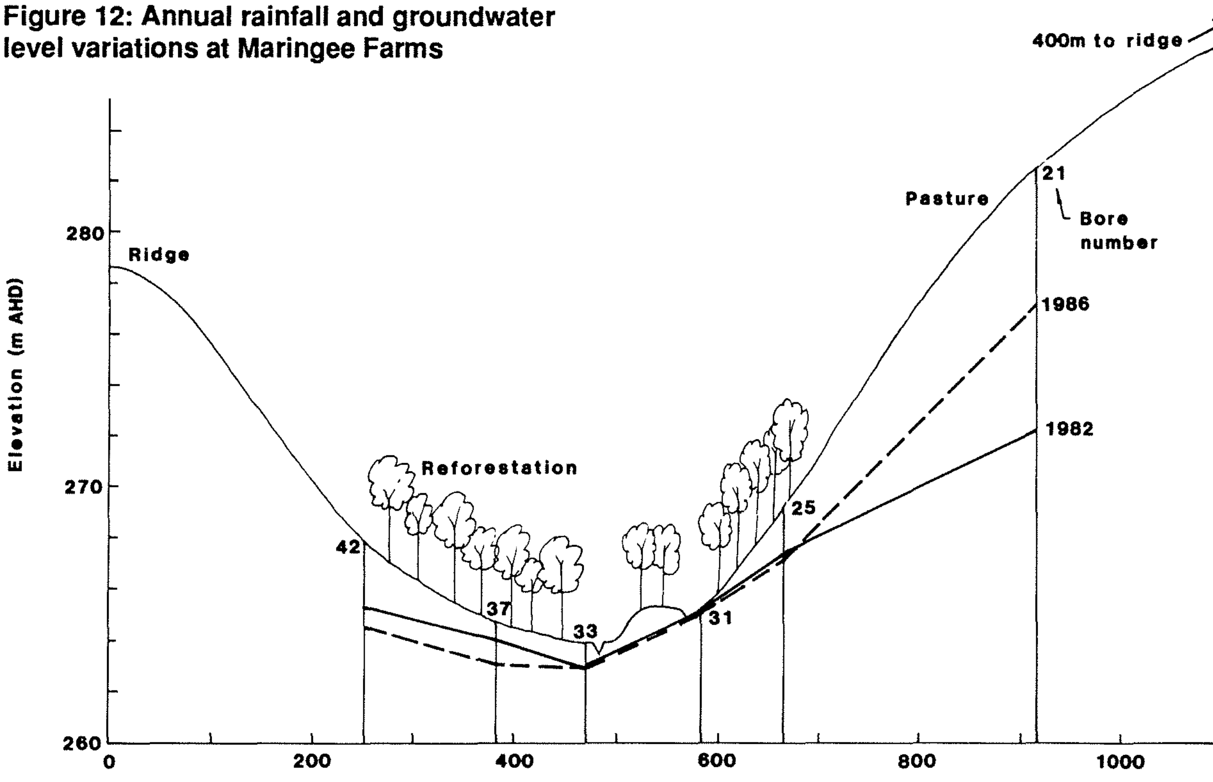


Figure 13: Comparison of valley cross-section potentiometric surfaces of 1982 and 1986 at Maringee Farms

with *P. radiata* in the Manjimup region (Malajczuk *et al.*, 1984) found that in the long term agroforestry can be substantially more profitable than a grazing enterprise alone. A disadvantage is the long wait for returns from the timber crop. This can be largely offset by planting only a small proportion of a farm at any one time and staggering plantings to spread out the effect of lost grazing. Compared with dense plantation forestry, agroforestry has the advantage that substantial returns from agriculture can be obtained while the trees are growing. This can be a very important benefit, especially for farmers who wish to be independent and finance tree growing themselves. Growing the trees at wide-spacing enables the farmer to continue to obtain an income from agriculture.

Levels of pasture production and livestock carried under various ages and densities of *P. radiata* agroforestry were determined at Flynn's Farm (Figure 7) by Anderson *et al.*, (1988) and are summarised in Table 6. High levels of agricultural production can be maintained in the early years of the plantation but it declines with age. Agricultural production is also sensitive to stand density, declining with higher stand density for a given age.

The wide-spaced method of tree growing also enables tree growing for timber production to be extended to areas with lower rainfall. The eastern parts of most water resource catchments receive too little rain to support extensive dense plantations of trees.

Research into wide-spaced eucalypt plantations has become prominent in recent years. This has come about for a number of reasons: farmers have a strong preference for eucalypts rather than pine; eucalypts can be planted on sites unsuitable for pine; the need to satisfy future demand for high quality hardwood sawlogs; and the potential of the eucalypt pulpwood industry.

Table 6: Pasture produced and livestock carried under various ages and densities of *P. radiata* agroforestry as a percentage of open pasture (after Anderson *et al.*, 1988)

Age (yrs)	Stand density (trees/ha)	Pasture produced (%)	Livestock carried (%)
6–7 *	0	100	100
	100	87	82
	300	76	73
20 **	0	100	100
	70	67	59
	150	39	24

Notes: * pruned to 4 m, ** pruned to 6 m

Table 7: Mean height, mean diameter at breast height over bark (DBHOB) and mean DBHOB increment of eucalypts at a density of 150 trees per hectare

	Height (m) (age 5.5 yrs)	DBHOB (cm) (age 6.5 yrs)	DBHOB increment (cm/yr) (age 5.5 to 6.5 yrs)
E. globulus	11.85	24.45	5.10
E. paniculata	7.55	14.30	2.65
E. muellerana	8.20	18.05	3.65
E. maculata	10.30	18.45	3.50
E. oreades	8.90	17.45	4.05
E. diversicolor	10.70	20.25	4.30

The objectives of management of wide-spaced eucalypt plantations are to produce high quality sawlogs in conjunction with pasture for grazing or cropping. Trials began in the late 1970s. Several eucalypts have exhibited fast growth rates and suitable form. Some growth data from a trial near Busselton are presented in Table 7 (Moore, 1988). It has also been found that the natural tendency of eucalypts to self-prune greatly reduces the cost of pruning compared with pine.

3.3.2 Salinity control aspects of wide-spaced plantations

The three experimental sites in which the salinity control aspects of wide-spaced plantations have been investigated are Flynn's Farm Agroforestry in Mundaring Weir catchment, Stene's Farm Agroforestry in Wellington Dam catchment and Boundain near Narrogin (Figure 7). At each site the principal objective has been to determine the extent to which groundwater level can be lowered for a range of stem densities. The lowering of groundwater levels is considered to be an indication of reducing groundwater solute discharge to streams. The relevant characteristics of the three sites are listed in Table 8. These characteristics and the experimental results are discussed for each site below.

Flynn's Farm Agroforestry

The Agroforestry site at Flynn's Farm covers an area of approximately 35 hectares (Figure 14). The site was divided into 32 one-hectare plots in which wide-spaced trees were planted at densities ranging from 380–1140 stems/ha in 1978. Commencing in 1982, the sites were progressively culled to densities of 75–225 stems/ha by 1986. The species planted were *P. radiata, P. pinaster* and *E. camaldulensis*. Six one hectare plots were left under pasture. Ten deep bores were installed in reforestation and two in pasture. Within the experimental catchment area, 51% of the site had been previously cleared for agriculture. The

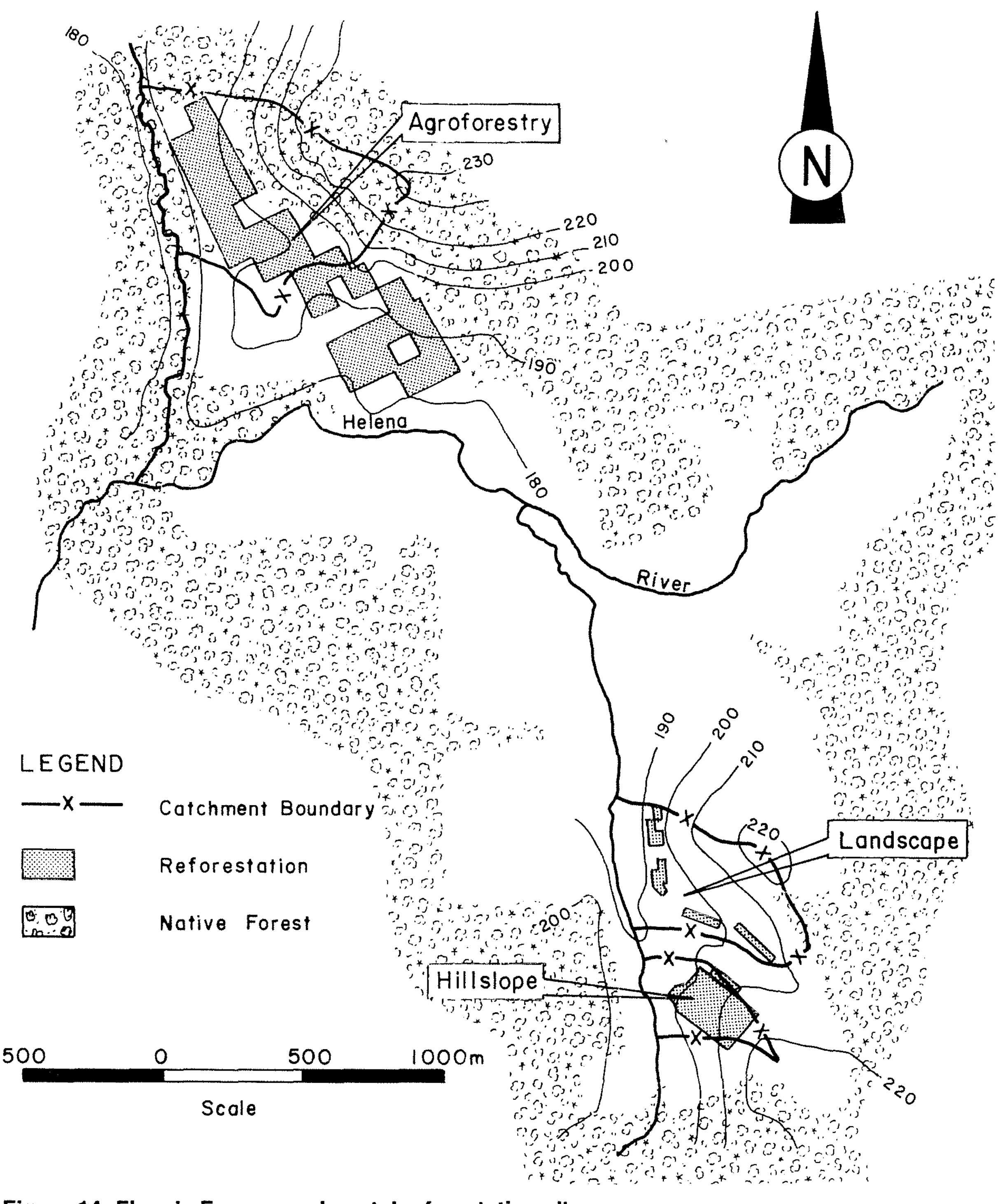


Figure 14: Flynn's Farm experimental reforestation sites

Table 8: Characteristics of agroforestry sites

Site	Annual rainfall (mm)	Planting year	Species planted	Initial planting density (stems/ha)	Stem density in 1986 (stems/ha)	Percent of site cleared (%)	Percent of cleared area replanted	Crown cover at 1987 (%)	Initial depth to water table (m)		Initial average salinity (mg/L TSS)	
									Mean	Range	Mean	Range
Flynn's Agroforestry	725	1978	*P. radiata* *P. pinaster* *E. camaldulensis*	380 to 1140	75 to 225	51	58	14	4.4	1.3 to 8.0	2400	130 to 8400
Stene's Agroforestry	725	1978	*E. calaldulensis* *E. sargentii* *E. wandoo*	1250	150 to 900	25	57	25	2.7	0.5 to 5.1	6600	250 to 11600
Boundain	505	1981	*E. globulus* *E. sargentii* *E. occidentalis* *E. camaldulensis* *C. glauca*	83 to 166	83 to 166	>95	21	25	1.3	?		2000 to 17000

clearing was located adjacent to, but to one side of the stream. The replanted area covered 58% of the cleared area and in 1987 had a crown cover of 14% (as determined by a crownometer similar to that used by Montana and Ezcurra, 1980). The site average minimum groundwater level at the time of planting was 4.4 m. The range in groundwater levels was 1.3 m–8.0 m. The initial average groundwater salinity was 2400 mg/L TSS. No seep area was evident at this site.

The results of the groundwater monitoring and rainfall for the period are summarised in Figure 15. The average minimum piezometric levels of the nine bores under plantation has shown a decline of 1.8 m over the period 1978–86. The main part of the decline (1.5 m) occurred within the first three years of planting which is largely attributed to the low rainfall during this period. Also during this pre-culling period the stem densities were considerably higher than after 1982. Over the 1978–86 period the groundwater level under pasture increased by 0.1 m. Throughout the study period the annual groundwater minima under both reforestation and pasture were responsive to annual rainfall. Rises in groundwater levels followed years of well-above-average rainfall (1981 and 1983) while falls followed years of below-average rainfall.

Stene's Farm Agroforestry

The Agroforestry site at Stene's Farm was planted in 1978 at a density of 1250 stems/ha. The site was divided into four plots spanning the valley floor and lower slopes (Figure 8). In 1981 the plots were thinned to give a range of densities of 150–900 stems/ha (Table 9). The crown covers at 1987 ranged from 20% to 31%. Plot A had a slightly higher crown cover than plot C, even though the stem density was lower (Table 9). In 1981 the site average minimum depth to groundwater was 2.7 m (range 0.5–5.1 m) and the site average groundwater salinity was 6600 mg/L

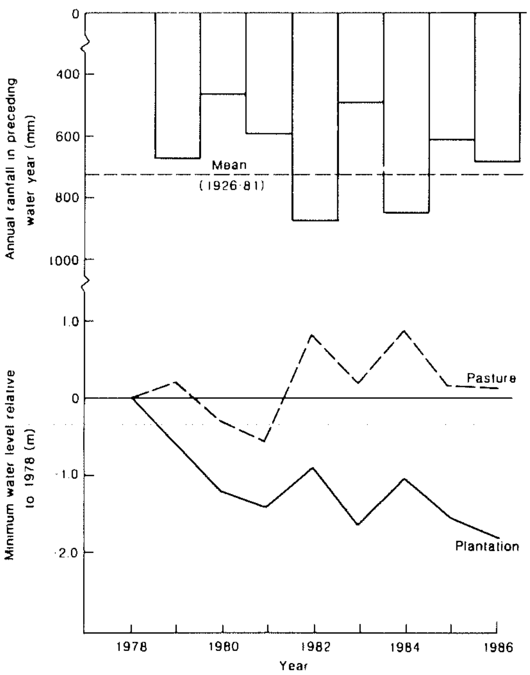


Figure 15: Annual rainfall and groundwater level variations at Flynn's Agroforestry site

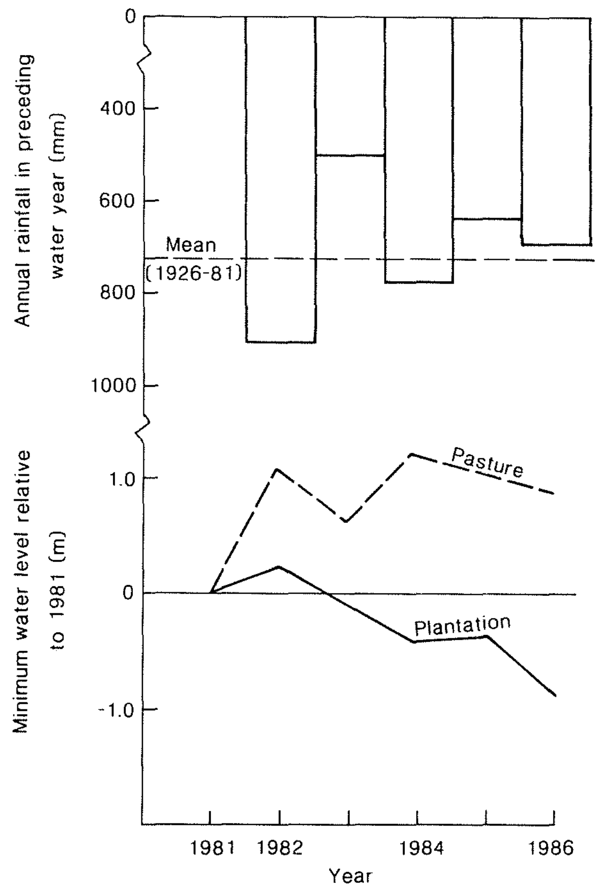


Figure 16: Annual rainfall and groundwater level variations at Stene's Farm Agroforestry site

TSS. Saline seeps were evident along the streamlines. This site was clearly somewhat more severely salt-affected and had higher potential for waterlogging than the Flynn's Farm Agroforestry site.

The species planted were *E. camaldulensis, E. sargentii* and *E. wandoo*. The proportion of area cleared for agriculture was 25%, of which 57% was replanted.

The annual minimum groundwater level over all four plots (8 bores) for the period 1981–1986 is shown in Figure 16. After an initial increase in groundwater level in 1982, there was a steady decline, with a net lowering of 0.8 m over the monitoring period. In contrast a set of nine bores in pasture on Stene's Farm showed a net increase in groundwater level of 0.8 m. This result implies that the agroforestry plantation was effective in reducing groundwater levels in these early years. The results for the four separate plots are shown in Table 9. Groundwater level reductions were observed on all plots. The smallest reductions were found on plot D which had the lowest crown cover and stem density.

Table 9: Groundwater level reductions on plots of varying stem density at Stene's Agroforestry site (1981–86)

Plot	Stem density (stem/ha)	Crown cover (%)	No. bores	Reduction in groundwater level (m)
A	600	31	2	1.31
B	300	22	2	1.28
C	900	28	2	0.77
D	150	20	2	0.48

Boundain

Boundain is located 25 km east of Narrogin (Figure 7) which has an average annual rainfall of 505 mm. The experimental site is a 22 ha subcatchment of the Yilliminning River. A survey in 1981 showed that about one hectare of the subcatchment was salt-affected but this area was expanding. In the valley floor salinity was associated with the regional groundwater system. Further upslope the development of salinity may have resulted from the presence of dolerite dykes or shallow basement rock. A saline water table occurred at a depth of about 1.3 m with salinities in the range 2000–17 000 mg/L TSS.

An agroforestry trial was established by the Department of Agriculture in June 1981 at the site adjacent to the expanding salt seep. Trees were planted at two densities, 166 stems/ha and 83 stems/ha, in 40 metre by 150 metre plots. Unplanted plots were included in the layout and all plots were replicated five times. On each plot there was a progression from moderately saline land downslope to non-saline land upslope. Tree species were chosen and planted according to the salinity hazard. *E. globulus* was planted on non-saline areas, *E. camaldulensis* was planted on areas where salt was encroaching, and *E. occidentalis* (flat-topped yate), *E. sargentii* (salt river gum) and *Casuarina glauca* (salt sheoak) were planted on the salt affected land. The total replanted area was 4.7 ha or 21% of the subcatchment.

Sixty-five groundwater bores were installed in the trial site. A comparison of annual minimum groundwater levels across the site at the time of planting and seven years after planting is shown in Figure 17a. The average depression of groundwater across the site was 0.9 m and the maximum depression was 1.9 m. The average groundwater depression beneath the reforestation stands was

1.0 m as compared to 0.25 m beneath the pasture control plots.

The change in groundwater levels over time for each treatment is shown in Figure 17b. In the first three years there was little indication of any lowering of the water table. During these years the plantations were young and rainfall was also slightly above average. After 1984 there were significant rates of water table decline beneath the reforested areas. The rate of decline was greater for the higher density plantings. There was also a small water table decline in the control plots. The period during which water tables declined coincided with years of below average rainfall. Over the period 1981-88 the mean annual rainfall was 8% below the long term average.

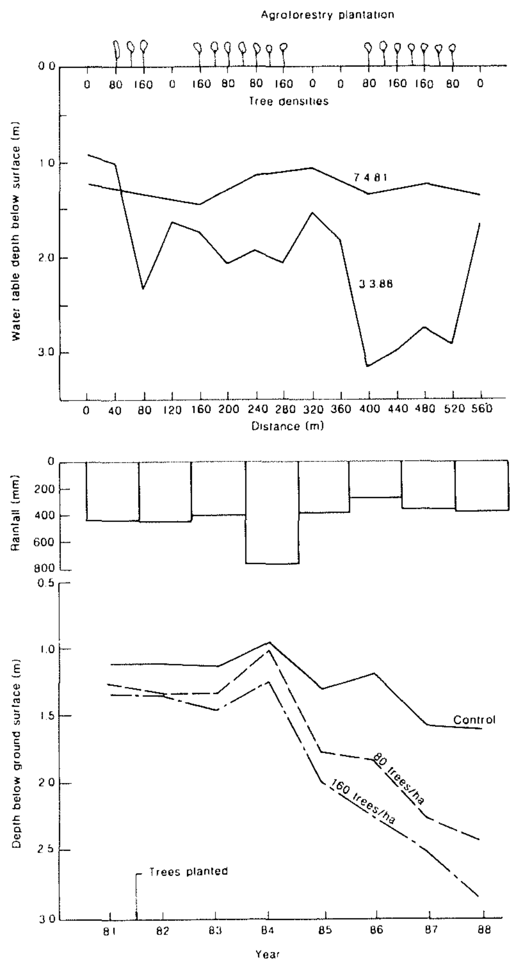


Figure 17: Groundwater and rainfall variations at Boundain: (a) comparison of groundwater levels across the site between 1981 and 1988 (b) annual rainfall and groundwater level variations beneath pasture and agroforestry plantations

Measurement of salt content through the soil profile over the period 1981–88 showed that under reforested areas salt content decreased from 0–0.75 m depth, increased from 0.75–2.25 m depth and remained about the same below 2.25 m depth. There was little change in the salt profile in the control plots.

The growth of *E. sargentii* and *Casuarina glauca* was found to be adversely affected by waterlogging.

3.4 Strip and Landscape Planting

Two tree planting strategies considered for salinity control at the commencement of the reforestation trials in the late 1970s were the strategic placement of forest strips (Strip planting) and isolated blocks (Landscape planting).

These schemes are particularly attractive to farmers because they allow unimpeded access (for machinery) to the agricultural land between the strips or blocks. The potential for timber production from strips is also attractive, although growth rates may be slightly less than wide-spaced plantations (R. Moore, pers. comm. 1988). Tree strips as shelterbelts are also a very useful management tool for wind erosion control and are being strongly promoted for this use on the south coast of Western Australia.

Three trial sites were established: a landscape planting on Flynn's Farm in 1978; a strip planting on Stene's Farm over the period 1976–78; and small block plantations at Bannister in 1976 (Figure 7). The details of these sites are given in Table 10 and the experimental results are presented individually below.

Flynn's Farm Landscape Planting

The layout of the Landscape plantings is shown in Figure 14. The area was previously totally cleared for agriculture and a relatively small proportion (8%) of the site was replanted. The blocks were located on the lower slopes just above saline seep areas. The blocks were of 50 by 30 metres. *E. wandoo, E. camaldulensis, P. pinaster* and *P. radiata* were planted at a stem density of 667 stems/ha. The average crown cover of the blocks had reached a high value (43%) by 1986. The initial average depth to groundwater over all the blocks was 2.1 m and the initial average salinity was 4600 mg/L TSS. The downslope seep area covered about 10% of the site. In 1983 additional upslope plantings took place on the ridge of this site but their hydrological impact is considered to be negligible over the period of groundwater analysis (1978–86).

Table 10: Characteristics of Landscape and Strip Plantings sites

Site	Annual rainfall (mm)	Planting year	Species planted	Initial planting density (stems/ha)	Stem density in 1986 (stems/ha)	Percent of site cleared (%)	Percent of cleared area replanted	Crown cover at 1987 (%)	Initial depth to water table (m)		Initial average salinity (mg/L TSS)	
									Mean	Range	Mean	Range
Flynn's Landscape	725	1978	*E. wandoo* *E. camaldulensis* *P. pinaster* *P. radiata*	667	500	98	8	43	2.1	0.5 to 3.7	4600	330 to 16600
Stene's Strip Plantings	725	1976 to 1978	*E. globulus* *E. camaldulensis* *P. radiata* *P. pinaster* *E. wandoo*	1200	600	31	14	47	2.7	0 to 9.9	7700	150 to 24600
Bannister	800	1976	25 species	816	?	83	14	?	?	2-8	5500*	1000 to 9600*

* data at 1985

The time trends of groundwater levels below the Landscape blocks and below pasture are shown in Figure 18. In the first four years there was little difference between the pasture and block plantings. Over the period 1982–86 the Landscape planting groundwater levels were slightly depressed relative to pasture. By 1986 there was a net groundwater table reduction of 0.2 m below the plantations and a net increase of 0.1 m below pasture. The minor impact of the plantings is considered to be due to inadequate planting area (see section 4.1).

Stene's Farm Strip Plantings

The design of the Strip Plantings at Stene's Farm is shown in Figure 8. About 31% of the site was cleared for agriculture between 1964 and 1970. Two salt seeps have developed on the river flat in recent years and appear to be extending. Strip plantings at the site were carried out over the period 1976–78 and included the species *E. globulus, E. camaldulensis, E. wandoo, P. radiata* and *P. pinaster*. There were three components to the planting strategy. Firstly a 40 m strip of trees was placed parallel to the road to 'control' downslope groundwater flow from south of the Collie-Williams road. Secondly strips were located around the salt seeps in an attempt to draw down water tables locally. Thirdly 30 m strips were placed upslope in a pattern to ensure that there were only small areas where the spacing between strips was greater than 200 m. The proportion of cleared area replanted was 14%.

The average crown cover of the strip plantings at 1987 was a high 47%. The initial average depth to groundwater was 2.7 m and the initial groundwater salinity was 7700 mg/L TSS. The site could thus be considered of moderate severity.

The response of the groundwater table beneath the strip plantings is compared to the response

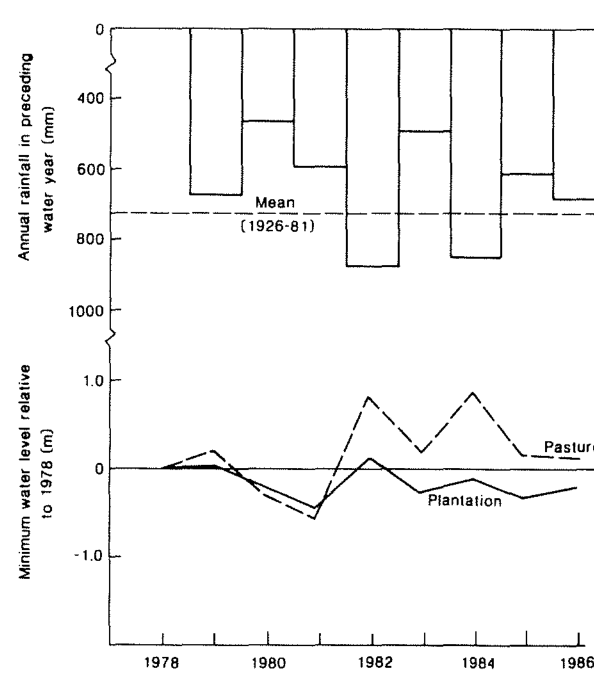


Figure 18: Annual rainfall and groundwater level variations at Flynn's Farm Landscape site

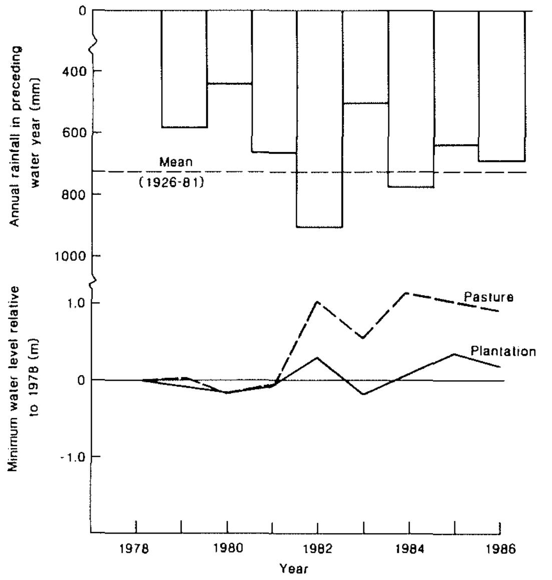


Figure 19: Annual rainfall and groundwater level variations at Stene's Farm Strip Plantings site

beneath pasture over the period 1978–86 in Figure 19. Under the strip plantings there was a small net increase in groundwater level of 0.2 m, while under pasture the increase was 0.8 m. The strip plantings have clearly been ineffective in reducing groundwater levels although they do appear to have reduced the rise which would have occurred under pasture. The relatively poor performance of the strip plantings as regards water table depression is again attributed to the small area planted (see section 4.1).

Bannister block planting

The Bannister site was selected for trial reforestation by CSIRO in 1975. There were two plantations, one upslope and one midslope (just above a saline seep), each covering about 6% of the experimental catchment area. Eighty-three per cent of the catchment was previously cleared for agriculture and so the plantations covered about 14% of the cleared land.

Twenty-five species were planted on the three catchments. Of these 16 are endemic to Western Australia and the others are natural dominants of open forests and woodlands of inland and coastal regions from south-east Queensland to Tasmania and South Australia. Reasons for the choice of species, including known salt tolerance in some instances, have been discussed by Biddiscombe *et al.* (1981).

There were two separate but concurrent trials at each locality. Trial A contained the species which were expected to perform the best at each location. Trial B contained promising species which had been less thoroughly tested. Each species plot contained 30 trees in trial A and 25 or 16 in trial B including 'guard' trees. In some plots the inner trees were surrounded by trees of another species. Spacing was on a 3.5 x 3.5 m grid (816 stems/ha) throughout. Species which established poorly from the first planting were replaced in 1977. Grazing was excluded for 18 months after the first planting, allowing the replaced trees six months without grazing. Subsequently all plantations were grazed periodically.

In 1976 twenty-two groundwater bores were installed. Over the period of monitoring (1976–1987) there was no observed reduction in groundwater levels under the plantations and no significant difference to groundwater levels under pasture (Figure 20). This result is attributed to the low proportion of area planted (see section 4.1).

Amongst a range of measurements taken at Bannister was the measurement of soil moisture profiles beneath pasture and various tree species within the plantations and remnant native clumps. In nearly all cases volumetric water content changes during a year were negligible beneath

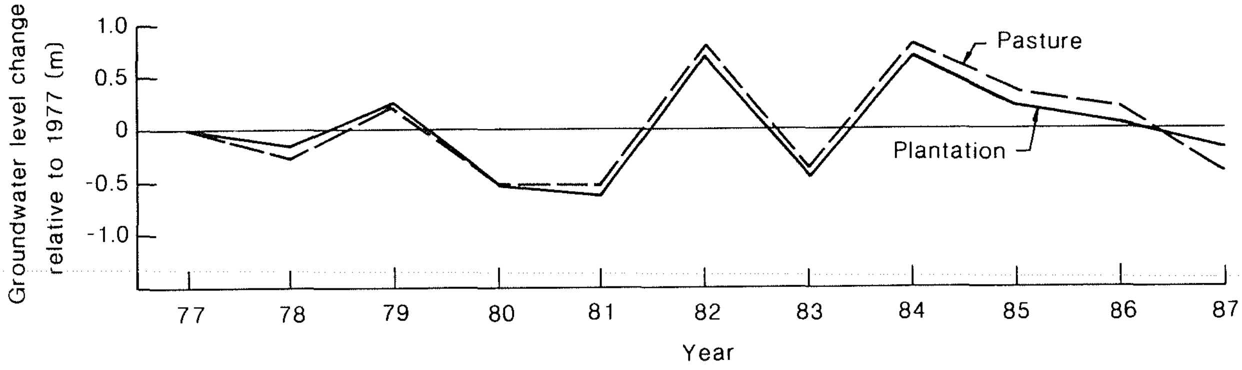


Figure 20: Annual groundwater level variations under reforestation and pasture at Bannister

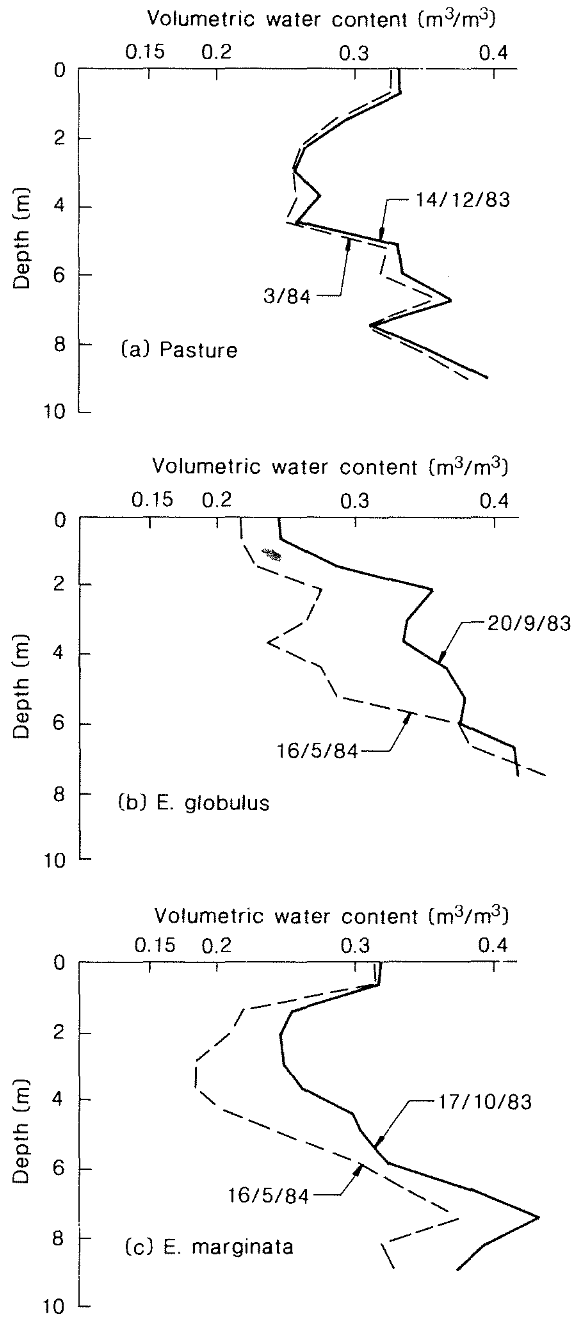


Figure 21: Annual maximum and minimum soil moisture profiles for pasture, *E. globulus* and *E. marginata*

pasture below a depth of 0.5 m. In contrast significant seasonal wetting and drying of the soil profile occurred under all tree species, and in some cases to depths approaching 10 metres. This demonstrated that trees were extracting considerable quantities of soil water during summer, whereas pasture was not, a conclusion also reached by transpiration measurements (section 3.1.2). The maximum and minimum soil moisture profiles within a year for pasture, *E. globulus* (plantation) and *E. marginata* (native clump) are shown in Figure 21.

3.5 Intensive Plantations

3.5.1 The potential of commercial intensive plantations for salinity control and timber production

The reforestation method for salinity control employed in the Wellington Dam catchment (see section 4.2) attached great importance to the water use capacity of the tree species used. This characteristic was required so that the area and density of tree planting, and the level of disruption to agriculture, might be minimised. Considerable work was done to identify species with superior water use. However the results were not conclusive (section 3.1.2), although species able to extract water against highly negative water potentials were identified (section 3.1.1). Most of these species were of little commercial value.

The approach of the Wellington reforestation programme which involves purchase of land and the use of non-commercial trees is costly and disruptive to farming. This situation could be improved by introducing economically attractive tree planting schemes.

Fortunately it appears that both the water use and growth performance of potentially commercial species are better than early assessments anticipated. Also, the success of the sharefarming concept has provided a model by which extensive voluntary planting of commercial tree crops by farmers could be undertaken.

A major criterion of commercial suitability should be that the product be saleable on large volume world markets since the prospective area for treatment of land and stream salinity is large (i.e. about 30–50% of the 650 000 ha of cleared farmland in the 600–900 mm rainfall area from south of Perth to just east of Albany). Local or even national markets are likely to be too small to absorb the yield from plantings on this scale; for example the local *P. radiata* market only requires growth in plantation area of 2000 ha/yr, far too little to have an impact on salinity at a regional scale.

Pine Plantations

Western Australia has a small local softwood industry. The area of present plantings total 50 000 ha with an annual increase of 2000 ha

(Department of Conservation and Land Management, 1987). The industry has developed to maintain timber supply in the face of a projected decline in the cut from native hardwood forests (Figure 22). Two main areas and species have been planted:

—Some 23 000 ha of *Pinus pinaster* have been established on native banksia woodland on the coastal plain north of Perth. Due to modest productivity and conflict with ground water supply no further new plantings are planned, and only the most productive areas will be considered for a second rotation.

—Some 27 000 ha of *Pinus radiata* has been established in the intermediate and high rainfall zones of the central and southern forest regions with a particular focus in the Blackwood Valley between Bridgetown and Nannup. This is a prime forestry region with long established forestry infrastructure. Plantations have been established predominantly on farmland purchased by the State or corporate investors. Some native forest areas have been converted to pine especially in the Donnybrook Sunkland region between Nannup and Busselton.

Historically there has been little serious consideration of the potential to relocate pine plantation forestry or redesign pine production systems to gain secondary water quality benefits. Relocation into the low rainfall zone has generally been considered to be beyond the productivity limits for pine and to be too distant from established infrastructure. There has also been some uncertainty as to the likely effectiveness of pines in establishing a water balance comparable with native forest in the plateau soil environment (Bartle and Shea, 1978).

However social pressures have forced a re-examination of land selection for pine afforestation. During the 1970s it became apparent that farming communities were opposed to an open-ended expansion of State pine plantation on farmland in some districts. The option of clearing native forest for pine planting also met with increasing resistance from the conservation movement and in 1983 a decision by the State Government closed off this option. Furthermore, the capital cost of land acquisition emerged as another problem in the economic environment of the 1980s. A less obtrusive, less capital demanding means of pine plantation establishment on farmland had to be found.

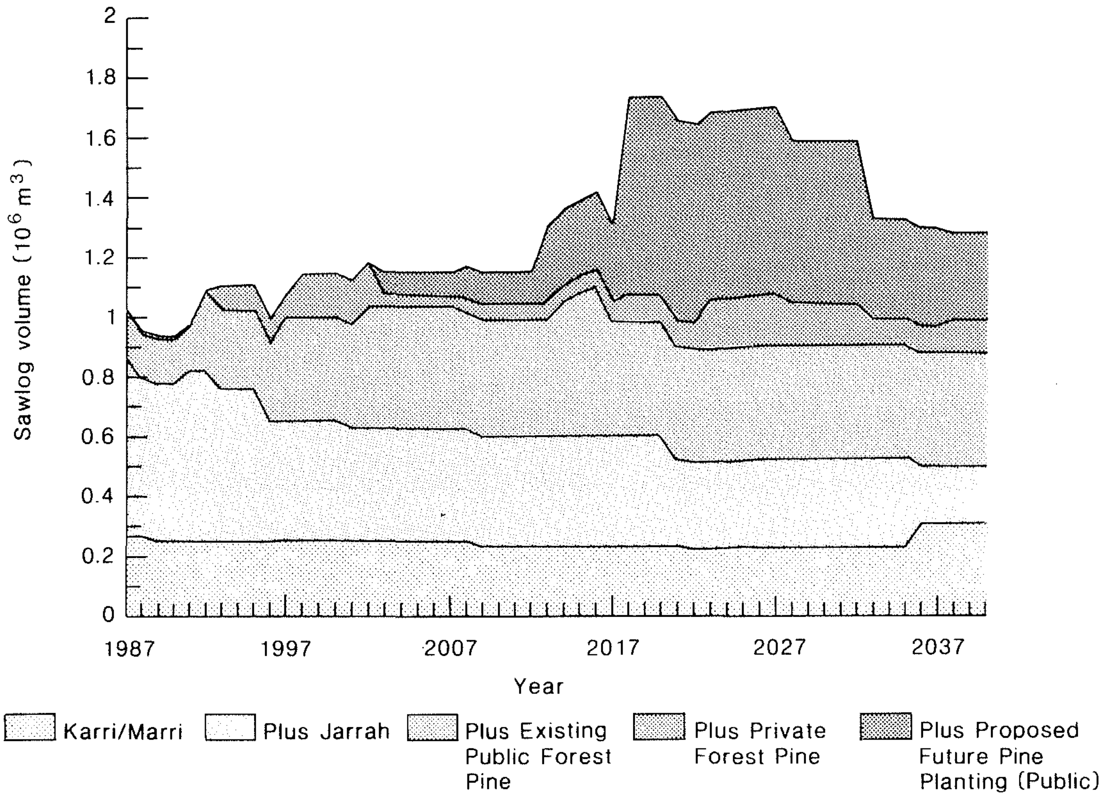


Figure 22: Long term projected supply of sawlogs from public and private forests

The independent Centre for Applied Business Research was commissioned to investigate means by which pines could be grown co-operatively with farmers (Treloar, 1984). This study concluded that pine production was economically competitive in comparison to other extensive agricultural crops in the Manjimup area, but that the distribution of costs and returns over time excluded it as an option for most farmers to undertake independently. The Department of Conservation and Land Management therefore developed the Softwood Sharefarming Scheme (Grant 1986). Under this scheme the State and the farmer contract to share establishment and management costs. The State underwrites expected future revenue, and, after covering its costs, pays to the farmer the discounted revenue surplus as an annuity and variable share of the final revenue. The scheme was not initially attractive to farmers in the Manjimup area where it was first offered. This was apparently partly due to the small property size and the perceived loss of flexibility given the minimum plantation size constraint of 40 ha.

This impasse forced CALM to look further afield. The Albany region was identified as the most prospective target area. Albany is a major regional centre and an appropriate location for the infrastructure required for a timber industry. Property sizes in the hinterland are much larger than around Manjimup. Though lying in the intermediate and low rainfall zone the more moderate temperatures and longer growing season of its southern coastal climate is much more favourable than the inland low rainfall zone climate further north. A rapid reconnaissance of the performance of *P. radiata* in various small plantings throughout the region indicated satisfactory growth potential, and a much reduced proneness to drought death in comparison to the west coast and inland areas with similar rainfall (Ellis, in prep.).

When publicised in the Albany region the Softwood Sharefarming Scheme generated considerable interest which opened the possibility of directing plantings into areas where the greatest water quality benefits might accrue. Thus the potential for a commercially driven treatment for salinity emerged. The need to quantify and demonstrate this potential and to combine it with recent advances in agricultural cropping and drainage methods linked in well with the need to arrest deteriorating surface water resources. This led to the development of the Denmark Integrated Catchment Management Project (see section 6).

Eucalypt Plantations

There is a large international trade in woodchips, woodpulp and paper. Australia is a net importer at a time when world market projections indicate a strong sellers market (Groome 1987). The potentially commercial eucalypt species showing promise include *E. globulus, E. saligna, E. botryoides* and *E. viminalis*. These species, native to tall forests in Victoria, Tasmania and New South Wales, have rapid early growth, and young trees in particular produce high quality fibre for paper manufacture.

There are sufficient scattered plantings to provide an indication of appropriate silvicultural practice and likely yield of *E. globulus*. Yields likely from good quality farmland range from 15 m^3/ha/yr for 600 mm rainfall to more than 30 m^3 /ha/yr at 1100 mm rainfall. Rotation lengths will vary from 7 to 14 years for the first cut and 5–10 years for subsequent coppice crops. At a projected sale price of $20/$m^3$ at the stump, the surplus of discounted revenue over costs can provide annuities under a sharefarming contract ranging from $80-240/ha/yr. These returns appear sufficient to be of interest to farmers.

The outlook for a major short-rotation eucalypt sharefarming industry appears very attractive. The State Government and the local timber industry have undertaken a full-scale feasibility study. The State Government recently announced that a Tree Trust would be established to operate a pulpwood industry on a commercial basis.

Using interim arrangements CALM planted some 2000 ha of *E. globulus* in 1988 and up to 5000 ha will be planted in 1989. Thereafter, the Tree Trust, if successfully established, is projected to plant 10 000 ha/yr to 1999.

3.5.2 Groundwater response to intensive plantations

There are two reforestation trial sites which give an indication of the potential of intensive plantations to lower the water table. The first site is referred to as the Hillslope planting and is located on Flynn's Farm and the second site is referred to as the Arboretum on Stene's Farm. The characteristics of the two sites are summarised in Table 11 and discussed individually below.

Hillslope planting

Prior to replanting at this site (Figure 14) all the native vegetation was cleared for agriculture. In 1978 and 1979 54% of the hillslope was planted to *E. camaldulensis* and *E. wandoo* at a 4 x 2

Table 11: Characteristics of intensive planting sites											
Site	Annual rainfall (mm)	Planting year	Species planted	Initial planting density (stems/ha)	Stem density in 1986 (stems/ha)	Percent of site cleared (%)	Percent of cleared area replanted	Crown cover at 1987 (%)	Initial depth to water table (m)		Initial average salinity (mg/L TSS)	
									Mean	Range	Mean	Range
Flynn's Hillslope	725	1978/79	*E. wandoo* *E. camaldulensis*	1250	1000	100	54	29	3.3	0.9 to 5.8	7400	2400 to 12100
Stene's Arboretum	725	1979	65 species	625	variable	35	70	39	7.1	1.2 to 19.4	5400	260 to 14100

metre spacing (1250 stems/ha). These species are not the currently favoured commercial species but they should give some indication of the groundwater response. The plantation covered most of the hillslope except for the lower slope and valley floor which formed an extensive saline seep. The stem density at 1986 had decreased to 1000 stems/ha approximately. The average crown cover on the site at 1987 was 29%. The initial depths to groundwater ranged from 5.8 metres at midslope to 0.9 metres at the downslope edge of the plantation. The initial average groundwater salinity at the site was 7400 mg/L TSS.

The response of the groundwater table beneath the plantation and pasture is compared for the period 1978–86 in Figure 23. Beneath the plantation a substantial reduction of 2.0 metres in the annual minimum water table depth occurred over the period. A very rapid fall in the water table occurred in the first three years of the plantation, probably brought about by the significantly lower than average rainfall. From 1981 onwards the decline in the water table depth was at a markedly slower rate. The nature and magnitude of the response was very similar to that of the Flynn's Farm Agroforestry site. Under both reforestation and pasture the water table was responsive to the previous year's rainfall. In the case of the pasture there was no net decrease in water table depth over the 1978–86 period.

Stene's Arboretum

Stene's Arboretum was established in 1979 to evaluate the growth and transpiration potential of 63 eucalypt and two pine species. The site was divided into 123 approximately 0.5 ha plots, each planted with a single species. A bore network was also established in 1979 to determine the groundwater response across the whole site. Agricultural clearing had been restricted to the lower slopes and valley floor, representing some 35% of the experimental catchment (Figure 8). The average initial depth to groundwater in the cleared area was 7.1 m but was highly variable across the site, ranging from 1.2–19.4 m. The average initial groundwater salinity was 5400 mg/L TSS.

The time trend in site average minimum groundwater level is shown in Figure 24. There was little net change in groundwater level in the first four years of planting (1979–82). However in the ensuing four years (1983–86) there was a rapid decline in water table depths, attaining a net reduction of 2.5 m by 1986. In comparison the groundwater response under pasture at Stene's Farm showed an increase of 0.8 m over the same period (1979–86). The depression of groundwater levels across the site over the whole period

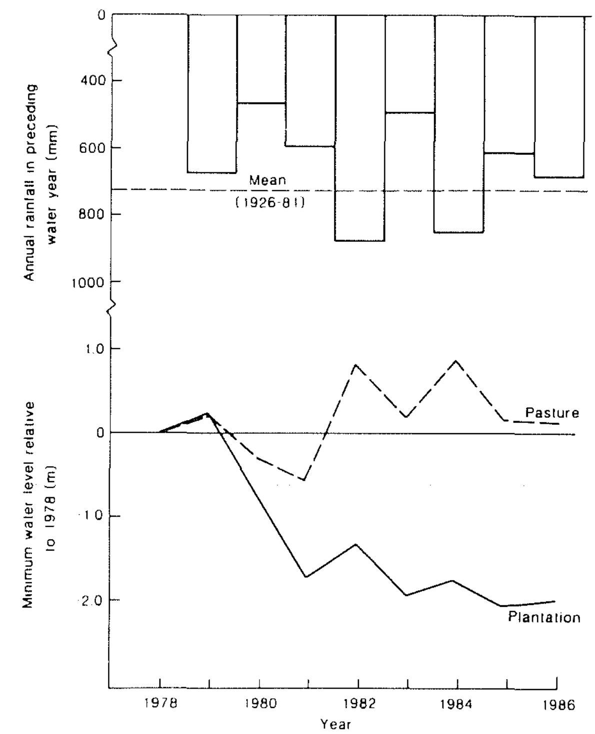


Figure 23: Annual rainfall and groundwater level variations at Flynn's Farm Hillslope site

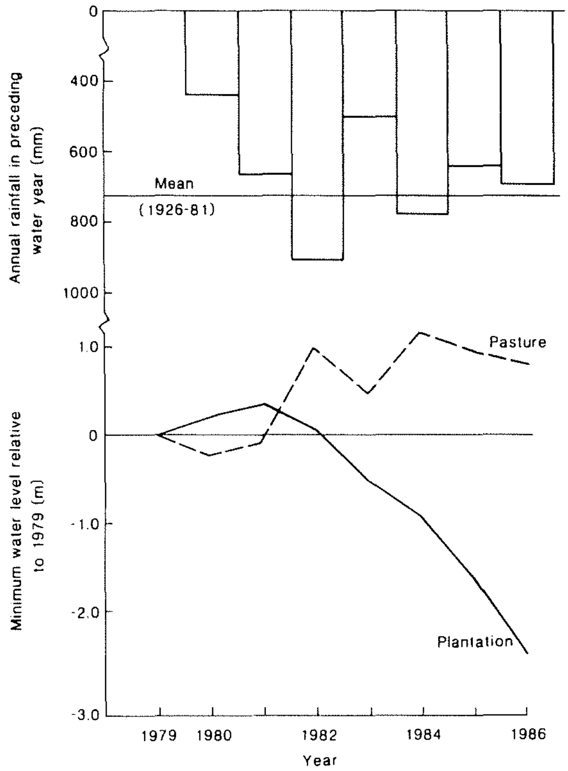


Figure 24: Annual rainfall and groundwater level variations at Stene's Arboretum

is shown clearly in Figure 25. The lowering of the water table has been greatest where depths to groundwater are smallest, and least where depths to groundwater are greatest. This implies that reforestation is more effective in lowering water tables where groundwaters are closer to the surface.

3.5.3 Stream yield, salinity and salt discharge response to intensive plantations

Streamflow and stream salinity measurements have been carried out at four experimental reforestation sites, Maringee Farms, Batalling Creek, Stenwood and Padbury Road catchments. The periods of record from the first three sites are insufficient to allow analysis of streamflow and stream salinity responses to reforestation. The data from Padbury Road catchment have been reported by Bell *et al.* (1987).

Padbury Road catchment is located midway between Bunbury and Manjimup, about 180 km south of Perth. The catchment is located on the eastern tributary of Balingup Brook. The long

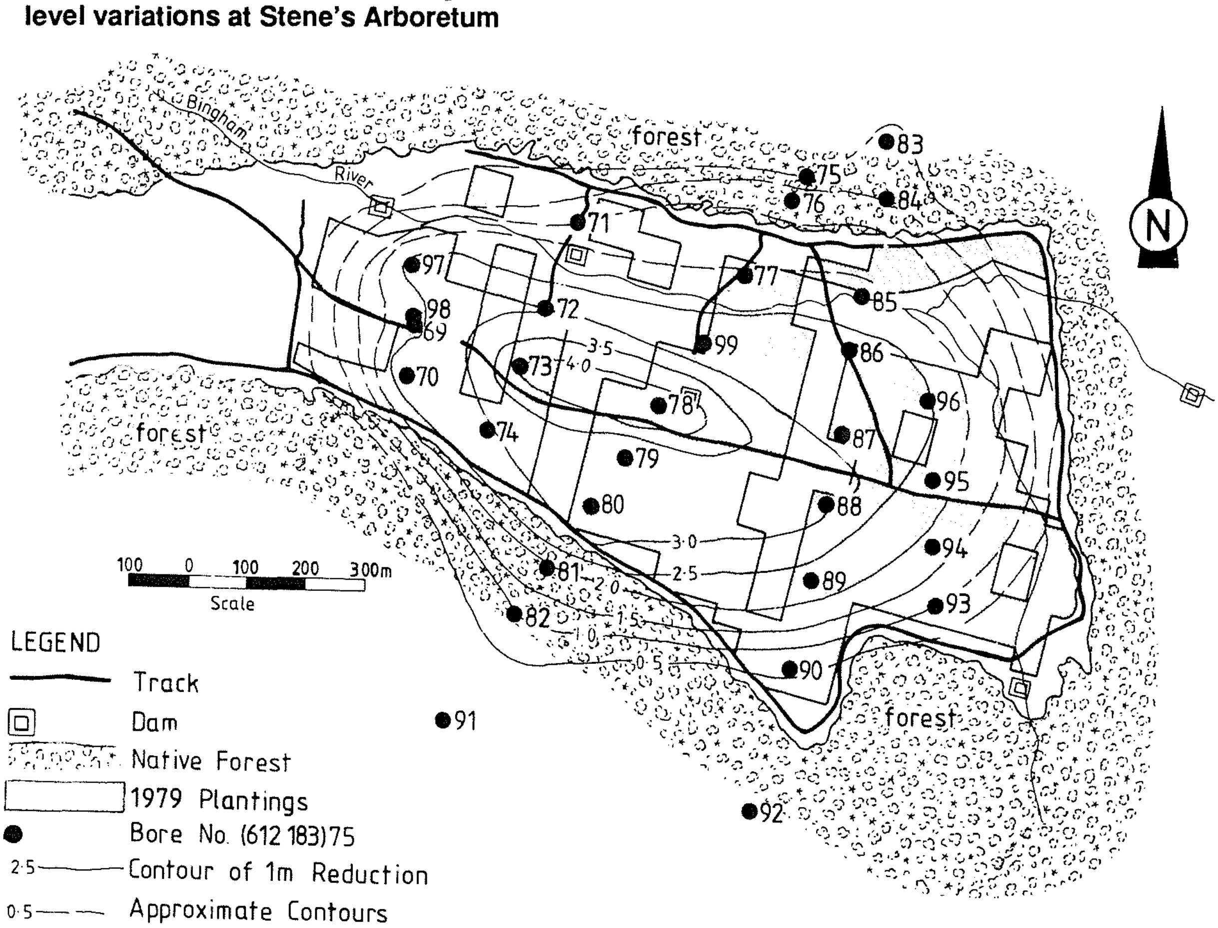


Figure 25: Reduction in groundwater level from 1979 to 1986 at Stene's Arboretum

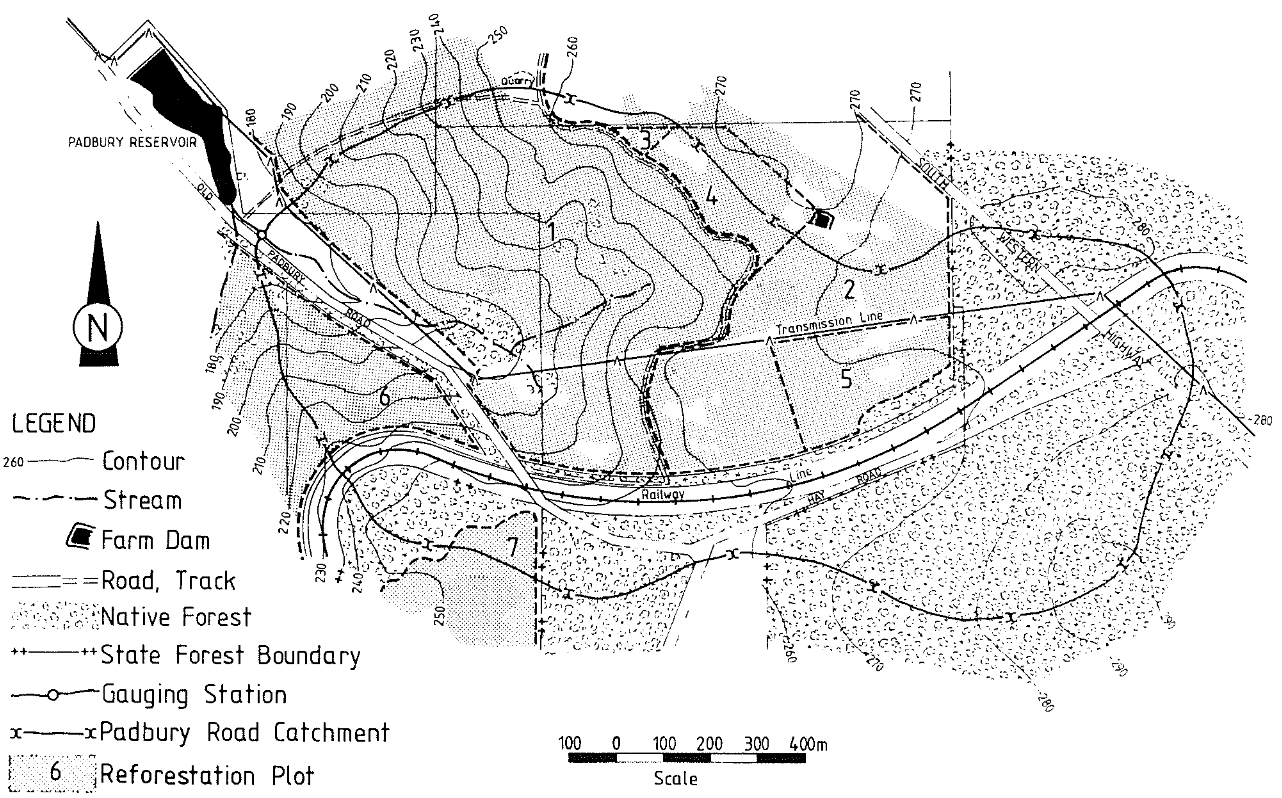


Figure 26: Padbury Road catchment showing reforestation

term mean annual rainfall for the catchment is 880 mm. The principal features of the catchment are shown in Figure 26. The catchment boundary (as shown in Figure 26) has been redefined since the report of Bell *et al.* (1987). The clearing history of the catchment is not well documented but by 1977 only 34% of the catchment remained under native forest. From 1960 to 1975 the salinity in the downstream Padbury reservoir increased from about 500 mg/L to 1000 mg/L TSS.

Between 1977 and 1983, 47% of the catchment was planted with pines and eucalypts. *Pinus radiata* was planted on 32% of the catchment, covering soils regarded as suitable for pines. *Eucalyptus globulus* and *E. resinifera* were planted on 14% of the catchment, covering the lower fertility lateritic uplands. The remaining 19% of the catchment is unforested. The unforested area included the valley floor which covered 3.5% of the catchment area.

The streamflow and stream salinity responses to reforestation of Padbury Road catchment described below are taken from the report of Bell *et al.* (1987).

Effects on streamflow

The stream gauging station (609 011) at the outlet of Padbury Road catchment did not become operational until February 1978 and so no pre-planting data were available. It was assumed, however, that reforestation would have had only a small effect on the water balance in its first four years of growth, and the period 1978–80 was considered as a 'pre-treatment' period.

The effect of reforestation on streamflow was evaluated by relating the Padbury Road catchment streamflow to rainfall at Balingup, and to streamflows at gauging stations on Ludlow River (610 007) and Thomson Brook (611 111). All three relationships showed the same pattern of a substantial decrease in streamflow since the first three years after reforestation. The magnitude of the decrease in streamflow was calculated as the difference between the observed values and values predicted by regressions for the 1978–80 period, and averaged for the three relationships (Table 12, column 5). The streamflow has continued to decrease over time, and by 1986 was only 9% of the predicted flow if the catchment was not reforested.

Effects on stream salinity

In streams of south-west Western Australia the flow-weighted mean annual stream salinity decreases as streamflow increases. The change in stream salinity of Padbury Road catchment due to reforestation was calculated as the difference between the observed salinity and the salinity given by the salinity-flow relationship for the flow that would have occurred had there been no reforestation. For example, in 1981 the observed flow was 118 mm and the observed salinity was 1140 mg/L. Without reforestation the streamflow would have been 157 mm (Table 12, column 4). For this flow the predicted salinity is 1201 mg/L. Reforestation therefore reduced stream salinity by 61 mg/L in this year (Table 12, column 8). However over the period 1981–86 stream salinities increased in four out of six years (Table 12, column 8) with the maximum increase being 531 mg/L. Stream salinities decreased in years with rainfall above 800 mm and increased in years with rainfall below 800 mm.

Effects on stream salt discharge

The annual stream salt discharge that would have occurred without reforestation is simply computed by multiplying the predicted streamflows and annual flow-weighted mean salinities derived above. Comparison of predicted and observed salt discharges shows that there has been a substantial decrease in salt discharge following the first four years of reforestation (Table 12, columns 9–11). Salt discharge has decreased over time, as did streamflow, to 10% of the predicted salt discharge without reforestation.

Discussion

Analysis of streamflow data from the Padbury Road catchment has shown that reforestation of the catchment to a level of 81% forest cover dramatically reduced streamflow and salt discharge in the first nine years following treatment. It also resulted in increased stream salinities in rainfall years below 800 mm/yr and decreased stream salinities in rainfall years above 800 mm/yr.

The continuous decrease in streamflow implies that there has been a continuous increase in evapotranspiration since reforestation. It thus appears that the evapotranspiration of the combination of *P. radiata* and *E. globulus* is substantially greater than pasture.

The decrease in salt discharge from the catchment is probably a reflection of both decreased streamflow and decreased groundwater discharge. Bell *et al.* (1987) argued that the salt discharge at a given flow decreased following reforestation, and that this occurred as a result of

Table 12: Streamflow, stream salinity and salt discharge of Padbury Road catchment in response to reforestation

Annual rainfall		Annual streamflow			Flow-weighted mean annual stream salinity			Annual salt discharge		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
year	Balingup (mm)	observed (mm)	predicted (mm)	change (mm)	observed (mg/L TSS)	predicted (mg/L TSS)	change (mg/L TSS)	observed[1] (t/ha)	predicted[2] (t/ha)	change (t/ha)
1978	844	196			1144			2.24		
1979	650	72			1772			1.28		
1980	926	157			1120			1.76		
1981	822	118	157	-39	1140	1201	-61	1.35	2.19	-.84
1982	708	39	94	-55	1867	1534	333	.73	1.65	-.92
1983	966	170	316	-146	710	860	-150	1.21	3.23	-2.02
1984	732	28	134	-106	1826	1295	531	.51	2.01	-1.50
1985	681	39	131	-92	1601	1309	292	.62	1.98	-1.36
1986	607	6.3	73	-67	2159	1730	429	.14	1.44	-1.30

[1] (observed streamflow x observed stream salinity)/10^6

[2] (predicted streamflow x predicted stream salinity)/10^6

reductions in groundwater levels and groundwater discharge. There were, however, no groundwater observations to support this argument, although the results described in the previous section (3.5.2) suggest that reductions in groundwater levels would be taking place, at least below the plantations.

3.6 Groundwater Salinity Response to Reforestation

3.6.1 Groundwater salinity analysis at Flynn's Farm and Stene's Farm sites

Groundwater salinity has been monitored in many of the bores installed at the experimental sites over the period since reforestation (Bell *et al.*, 1988). Most of the bores were only partially slotted for water intake, usually near the base of the bore. Where the bore is sunk deep below the water table, water in the bore will rise above the level of the slotted screen. The sampling procedure for salinity did not involve removing the standing head of water. This means that the salinity data may not accurately represent the salinity of the aquifer for bores with a standing head. Moreover, the groundwater salinity measured in such bores, even if pumped prior to sampling, may not reflect the salinity at the water table, which is the more appropriate value when considering groundwater extraction by trees. In a number of the bores, however, the water tables intersected the slotted screens (or were very close to the screens) over the period of measurement. Samples taken from these bores would genuinely reflect the groundwater salinity in the aquifer at the water table. Thus the analysis of groundwater salinity variation has been restricted to such bores. In this category were eight bores in pasture (3 Flynn's Farm Landscape, 5 Stene's Farm Strip Plantings) and 15 bores under reforestation (1 Flynn's Farm Landscape, 6 Flynn's Farm Agroforestry, 2 Stene's Farm Strip Plantings, 6 Stene's Arboretum) which have been monitored since 1978/79.

Since the number of bores at each site is inadequate to represent the behaviour of each site, the data have been averaged in two groups to represent groundwater salinity variation under pasture and reforestation. The results are shown in Figure 27. Since differences in bore salinities were of more than an order of magnitude, both arithmetic means and geometric means are presented. The

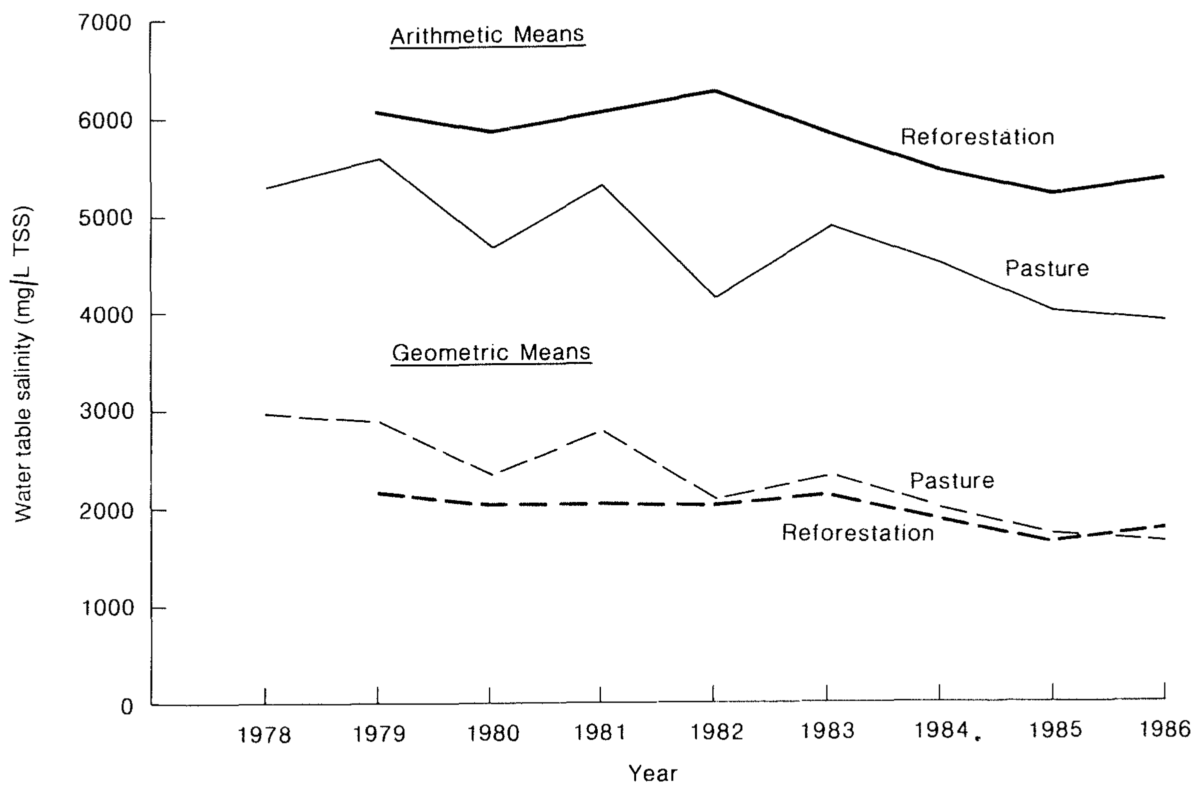


Figure 27: Averaged groundwater salinity trends beneath pasture and reforestation at Flynn's and Stene's Farms

arithmetic mean is biased towards the high salinity bore variations. The geometric mean gives a more equal weighting to the variations of all bores. For both means, the groundwater salinity has reduced under both pasture and reforestation over the period of measurement. For pasture the net reduction over the period 1979–86 has been 32% for the arithmetic mean and 43% for the geometric mean. For reforestation the corresponding groundwater salinity reductions over the same period have been 12% and 11%.

3.6.2 Groundwater salinity analysis at Boundain

At Boundain, shallow groundwater sampling bores were installed at 25 m spacing down the centre of each pasture and reforestation plot. Thirty seven bores were installed in 1981 to an average 3.5 m depth, with slotting over the bottom 1–2 m. A further 28 bores were installed in 1983 to 3 m depth with slotting over the bottom 1.5 m. Due to a lowering of the water table, the bores were re-installed to greater depths in 1988. Salinity sampling was carried out by first removing about two volumes of bore water to ensure the measured salinity was representative of the aquifer.

The groundwater salinity variation of a number of typical bores is shown in Figure 28. During the monitored period the groundwater salinity below reforestation generally increased, while below pasture groundwater salinity decreased or remained static. There is no obvious explanation why groundwater salinity beneath reforestation increased at this site but not at the other sites, although rainfall may be a factor.

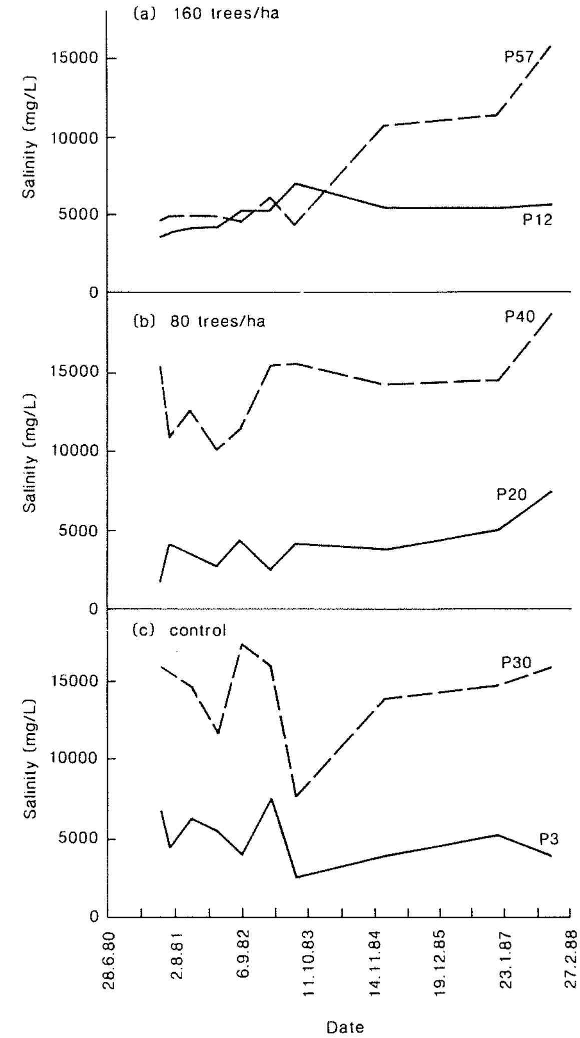


Figure 28: Groundwater salinity trends of typical bores under pasture and reforestation at Boundain

3.7 Water Resource Implications of Large-Scale Commercial Plantations

Analysis of salt discharge in the Padbury Road catchment following reforestation by pines and eucalypts showed that salt discharge decreased by 90% after nine years. This result is potentially very significant for salinity control when large-scale commercial plantations are proposed in water resource catchments which span high to low rainfall areas. It is well documented that the low rainfall areas, where substantial clearing for agriculture has taken place, produce a high proportion of the catchment salt discharge, but a small proportion of the catchment streamflow. The converse is true for the high rainfall area of the catchment. Reforestation of cleared areas within the low rainfall zone would significantly reduce the total salt discharge from the catchment without significantly decreasing the total streamflow. On the other hand reforestation in high rainfall areas would significantly reduce streamflow but not salt discharge, and stream salinity would increase.

The above arguments were supported by a quantitative analysis of the impact of establishing plantations in the Wellington Dam catchment and the Warren catchment (Bell *et al.*, 1987). Comparisons were made between reforestation of cleared areas with rainfall above and below 900 mm/yr. Model predictions showed that there would only be a salinity benefit when reforestation was carried out in areas below 900 mm/yr rainfall. Tree plantations in areas above 900 mm/yr rainfall were predicted to significantly reduce catchment water yield while at the same time increasing stream salinity.

4. *Experience with Operational Catchment Reforestation*

4.1 Requirements of Reforestation Area, Density and Layout

4.1.1 Introduction

At the outset of operational catchment reforestation on the Wellington Dam catchment estimates were required of the area and density of plantation required to reduce groundwater tables. The estimates made at that time were based on the simple water balance models of Peck (1976) which suggested that only 10–15% of the cleared area need be reforested in the 600–900 mm/yr rainfall zone. A number of reforestation trials were established with plantation areas of this order, which showed that these areas were insufficient to lower the water table (section 3). Operational plantings on the Wellington Dam catchment were designed to cover 30–40% of the cleared land to account for the uncertainties associated with the early estimates. Four methods of determining reforestation area and distribution for salinity control have recently been discussed by Schofield (1988), three of which are summarised here.

4.1.2 Regression methods

The first method derives empirical regressions relating depression of water table to plantation area and density, based on experimental data from the reforestation trials. Only regressions involving rates of water table change beneath reforestation were considered. Two linear regressions were calculated. The first is a regression of rate of water table change beneath reforestation relative to pasture on proportion of cleared area reforested. The regression is shown in Figure 29a. The regression is seen to have a high r^2 (= 0.97) and a high statistical significance ($p \sim 0.001$). Over the experimental period (1979–1986), groundwater levels under pasture rose 70 mm/yr (average of Flynn's and Stene's Farm sites). On the basis of the regression of Figure 29a, 11% of cleared area would need to be reforested to maintain groundwater levels constant under reforestation. Thus sites with low area plantings (Flynn's Landscape and Stene's Strip Plantings) would not be expected to significantly lower groundwater levels beneath reforestation relative to the ground surface. To lower the groundwater level beneath reforestation at 200 mm/yr relative to the ground surface would require 46% of the cleared area to be reforested.

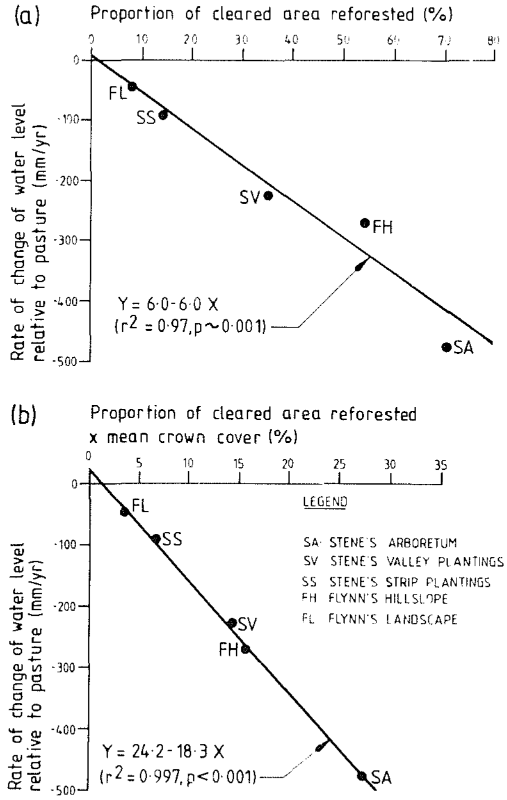


Figure 29: Dependence of mean rate of change of minimum groundwater level under reforestation relative to the minimum level under pasture on

(a) proportion of cleared area replanted and

(b) product of the proportion of the cleared landscape replanted and mean crown cover of reforestation

The mean annual rainfall over the experimental period was 10% below the long term average. Under average rainfall conditions groundwater levels under pasture were predicted to rise at 340 mm/yr at Flynn's Farm and Stene's Farm (R.W. Bell, pers. comm. 1989). To maintain the groundwater level constant beneath reforestation under these conditions would require 58% of the cleared land to be replanted, and to lower the water table at 200 mm/yr would require 91% of the cleared land to be replanted. A substantially longer data set which included higher rainfall years is required to determine a more valid regression applicable to average rainfall conditions.

The second regression sought to take account of crown cover and reforestation area, as suggested by Bell *et al.*, (1988). The regression of rate of water table change beneath reforestation relative to pasture on the product of proportion of cleared area replanted and crown cover is shown in Fig. 29b. The regression again has high r^2 (= 0.99) and high significance ($p<0.001$). This result is useful when deciding on area and planting density of reforestation, particularly when considering wide-spaced and close-spaced alternatives whose eventual crown covers are likely to be significantly different. As an example, to lower the groundwater level beneath reforestation relative to pasture at a rate of 340 mm/yr would require the product of proportion of cleared area reforested and crown cover to be 20%. This could be achieved, for example, by planting 100% of the area at 20% crown cover or 40% of the area at 50% crown cover.

The above regressions appear to be a useful approach for local conditions. The regressions are however based on data from sites with similar rainfall conditions (about 725 mm/yr) and cannot therefore be reliably used for significantly different rainfall areas. Also, no account has been taken of the effects of the transpiration of the reforestation stands changing with age.

4.1.3 Water balance method

The second method involves a more detailed analysis of the water balance approach (Schofield, 1988). The situation modelled is illustrated in Figure 30. It was assumed that the native forest was partly cleared in the valley but not on the upper slopes, as is usually the case in the 600–900 mm/yr rainfall zone of south-west Western Australia. In this example it was further assumed that there was no reforestation on the seep area. In order to lower the water table at a rate of Z mm/yr it was found that the required area was

$$A_r = \frac{E_f(1- A_f) + A_s(E_c- E_s) - E_c(1- A_f) + \Theta^* Z}{E_r - E_c} \quad (1)$$

where:

E_f = annual evaporation from native forest

E_s = annual evaporation from seep

E_c = annual evaporation from agriculture

E_r = annual evaporation from reforestation

A_f = area of remnant native forest

A_s = area of seep

Θ^* = change in soil water content following desaturation.

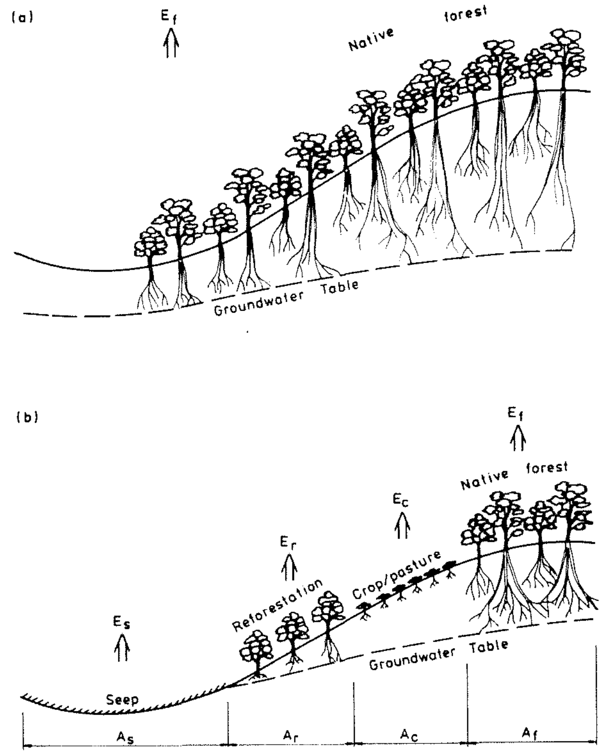


Figure 30: Conceptual illustrations for water balance models

Using the values of the above variables determined in Western Australia for an area of annual rainfall of 750 mm/yr:

E_f = 734 mm/yr,

E_s = 150 mm/yr,

E_c = 390 mm/yr,

E_r = 1870 mm/yr,

A_f = 34%,

A_s = 16%,

Θ^* = 0.25 m^3/m^3,

it was calculated that the area of reforestation required to decrease the water table at a rate of 200 mm/yr is 21% of the total catchment area or 32% of the area of clearing. This is significantly less than the value implied by the regression method (Figure 29a), but the result is strongly sensitive to the value taken for E_r. The range of reforestation area required for different reforestation transpiration rates is shown in Figure 31, using the same values of variables given above (except E_r). Figure 31 indicates that if annual reforestation transpiration was 1020 mm/yr, then 100% of the cleared area would need to be reforested to achieve a lowering of the water table of 200 mm/yr. A number of other examples were discussed by Schofield (1988).

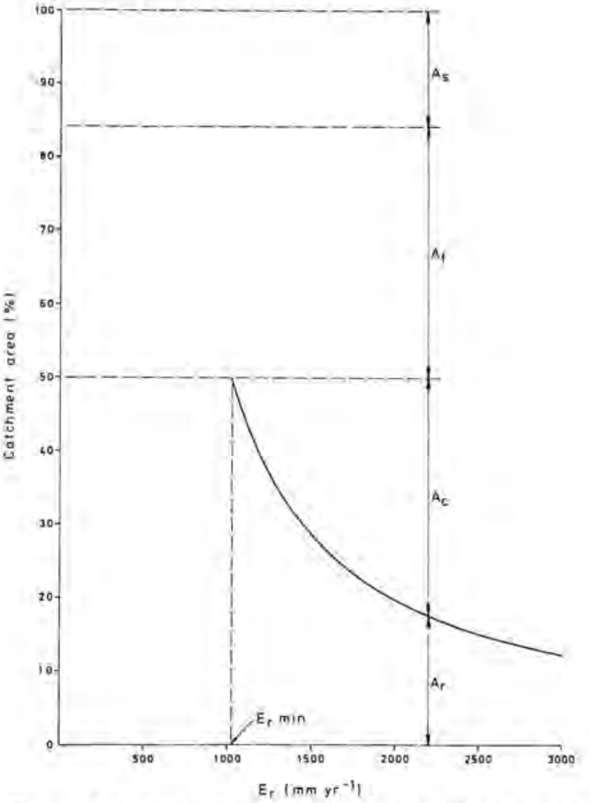


Figure 31: Required area of reforestation to meet a water balance criterion for a range of reforestation transpiration rates

4.1.4 Groundwater modelling approach

The realisation that vegetation strategies exert salinity control by limiting input or extracting water directly from the deep groundwater system led to the approach of groundwater modelling in reforestation design. It was also appreciated that the groundwater discharge response to a particular vegetation layout would depend to some extent on the aquifer properties (saturated hydraulic conductivity and storage coefficient) and bedrock topography. It was envisaged that groundwater modelling could lead to more effective vegetation layouts and also determine the groundwater response times for specific cases.

The groundwater model used was essentially that described by Prickett and Lonnquist (1971). Applications of the model to clearing and reforestation have been reported by Hookey and Loh (1985 a,b,c,d) and Hookey (1987). The model employs a finite difference method. An x-y grid is superimposed over the catchment and may be of variable spacing. The change in groundwater level, or hydraulic head, in each grid cell is the summation of groundwater flow rates to or from adjoining cells plus vertical recharge through the unsaturated zone or discharge via transpiration. When groundwater levels rise above the ground surface they are considered to be discharging as a seep. In this way the model can simulate the seepage area and seepage rate in a catchment.

Application of the model requires knowledge of the saturated hydraulic conductivity and storage coefficient of the aquifer, the initial groundwater level in relation to bedrock and the soil surface, and groundwater recharge and discharge rates. Each of these variables should be specified for each grid cell. Surface topography data can be adequately procured from 1:10 000 scale maps with 2 m contours. Bedrock topography is somewhat more difficult to obtain for the deep (~30 m) lateritic profiles, requiring either seismic surveys or intensive drilling. Saturated hydraulic conductivity (or transmissivity) and storage coefficient can be obtained from pump tests or bore slug tests.

Agricultural clearing has been clearly shown to increase groundwater recharge. Grid cells on which forest has been cleared were assumed to undergo continuous, constant groundwater recharge. Recharge rates may be determined from analysis of rising piezometric levels (Peck and Williamson, 1987) or analysis of soil chloride distributions (Johnston, 1987).

In areas which had been reforested with phreatophytes, groundwater would be continuously extracted. It was assumed that the rate of groundwater extraction decreased with depth. The maximum rate of groundwater extraction was increased linearly from zero at the time of planting to a maximum (E_{max}) after 10 years of growth. Over the same period the groundwater recharge was decreased linearly to zero. E_{max} was specified as that amount of groundwater extraction by reforestation necessary to consume the groundwater recharge (R) beneath cleared areas (Hookey and Loh, 1985a). This groundwater balance implies:

$$E_{max} A_r = R A_c$$

$$\text{or} \quad E_{max} = \frac{A_c}{A_r} R \qquad (2)$$

where A_c is the area cleared. Thus it is assumed that the proportion of area to be planted (A_r) has been previously specified. The model can then be used to determine the time response of the groundwater system to various reforestation layouts and so determine the optimum layout. Predictions can also be made of decreases in seepage area and groundwater discharge over time. Examples of the application of this approach to specific sites are given by Hookey and Loh (1985a,b,c,d) and Hookey (1987). Application of the model as a general technique in reforestation design requires assuming values for some key parameters (e.g. depth to bedrock, saturated hydraulic conductivity and storage coefficient) because they are too expensive to obtain at each individual site. Despite these limitations, groundwater modelling has been found to be a useful practical tool.

4.2 Wellington Dam Catchment Project

4.2.1 Introduction

Wellington Reservoir has the largest water yield of any individual reservoir in the south-west of Western Australia (approximately 100 x $10^6 m^3$). The continued increase in its inflow salinity has necessitated an active programme of catchment management and rehabilitation. The catchment

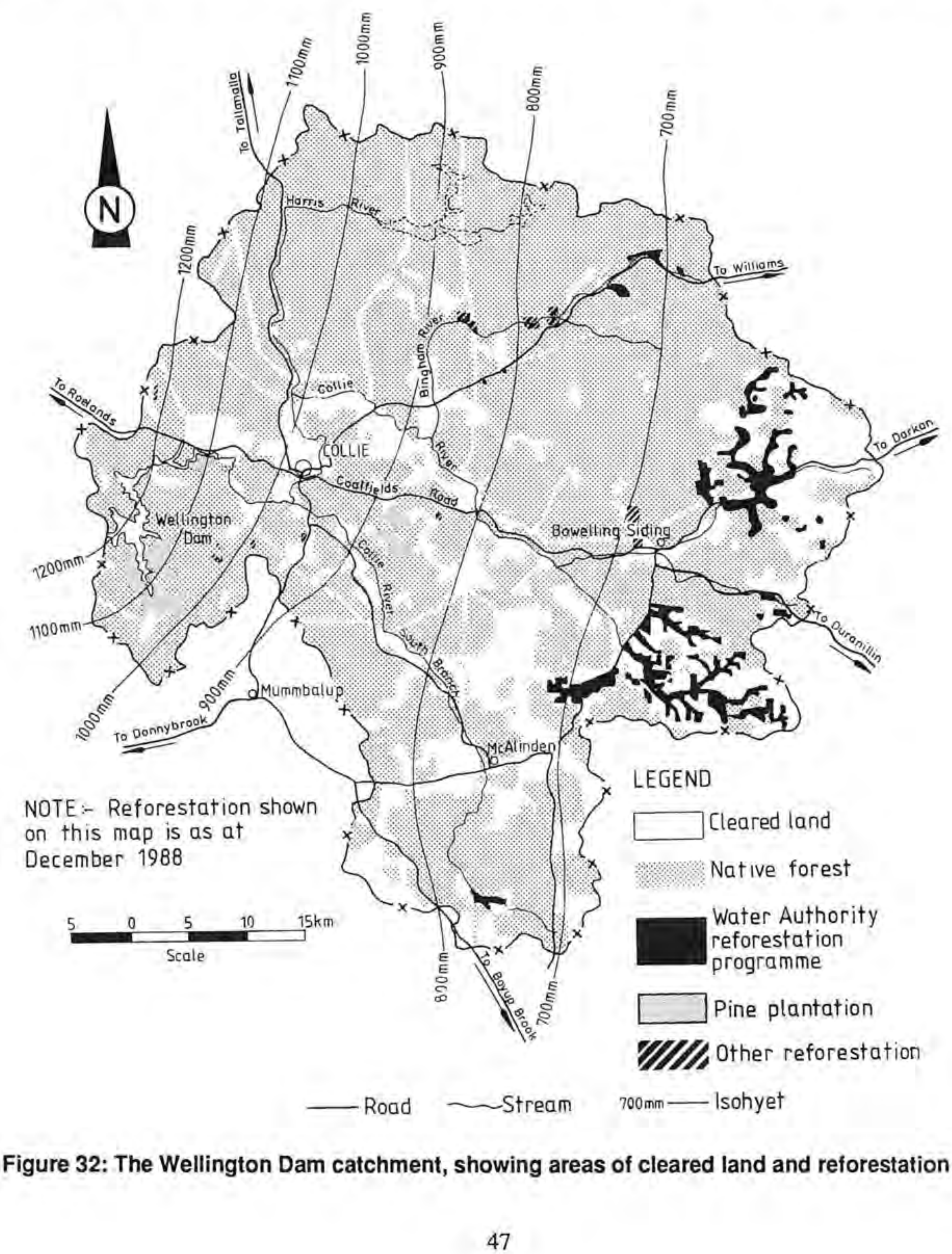


Figure 32: The Wellington Dam catchment, showing areas of cleared land and reforestation

spans a rainfall range from over 1200 mm/yr in the west to 600 mm/yr in the east of the catchment (Figure 32). Clearing of some of the original jarrah and wandoo forest in the 600 to 900 mm rainfall zone for agricultural development has resulted in major increases in stream salinity. This section summarises the history of stream salinity increases, and the catchment management measures introduced to minimise these increases.

4.2.2 Early clearing history and subsequent increases in stream salinity

Prior to agricultural development the salinity of the Collie River at Wellington Dam has been estimated to be between 200 and 250 mg/L. Agricultural development commenced at the turn of the century and expanded slowly over the following 30 years. No salinity problem was evident when the small irrigation dam was constructed in 1933. Growth in agricultural development virtually ceased through the depression years and it was not until the 1950s that agricultural development again expanded. To service increased demand for both irrigation on the coastal plain, and water supply in the wheatbelt towns of the Great Southern District, Wellington Dam was raised to its current height during the late 1950s. By this time serious salinity deterioration was apparent on small streams in the headwaters of the catchment and in 1961 the State Government, through administrative action, prevented further alienation of Crown land in the catchment.

In the late 1950s land clearing accelerated and extended upslope from the valleys where most of the early clearing had occurred. This was reflected in increased salinity through the late 1960s and early 1970s. By 1972/73 average inflow salinity was about 540 mg/L and was increasing at 22 mg/L per year. In the dry year of 1972/73 the inflow salinity was 685 mg/L. The trend in the inflow salinity (adjusted to a median inflow year) over the last 40 years is shown in Figure 33.

4.2.3 Clearing controls and the effects of past clearing

Realising the seriousness of the then current salinity levels and recognising that the full effect of

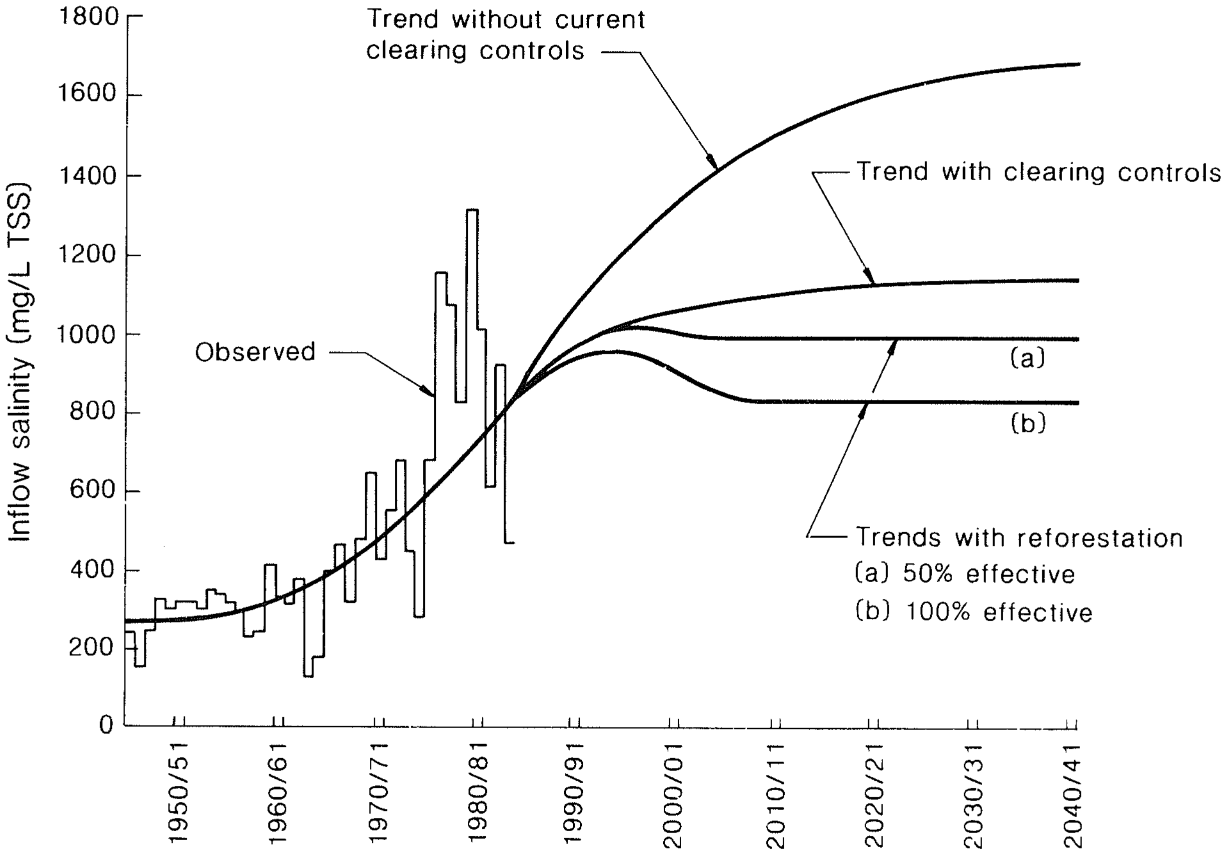


Figure 33:
Observed and predicted inflow salinities to Wellington Dam for various salinity control measures

past clearing was not yet reflected in the inflow salinity at that time, the State Government introduced legislation to control further clearing for agriculture in November 1976. The Country Areas Water Supply Act was amended to prohibit unlicenced clearing on the catchment. While small scale, essential clearing is licenced, large scale agricultural development is not permitted. Farmers affected can claim compensation for their inability to further develop their farm enterprise. Application of the legislation has effectively held the level of clearing to 64 000 ha or 23% of the total catchment and has avoided the expansion of agriculture to a possible 100 000 ha or 35% of the total catchment.

A means of predicting the effects of clearing on inflow salinity was developed by the mid-1970s. Prediction at the time indicated that if the level of clearing was maintained at the 1976 level the salinity of inflow in a median year would reach a maximum of about 1100 mg/L TSS. Subsequent detailed groundwater simulation studies support the original estimates. The groundwater simulations indicate that the salinity in a median inflow year would reach a maximum of 1150 mg/L TSS in 2040, in the absence of reforestation (Figure 33). In a dry year (10 percentile inflow) the inflow salinity could reach 1900 mg/L TSS by 2040.

4.2.4 The reforestation programme and predicted salinity improvements

While the clearing control legislation has had a major effect in minimising further deterioration in reservoir salinity levels, estimates of the full effect of clearing current at the time of the legislation indicated the quality of both town water and irrigation supplies would eventually become unacceptable, particularly in dry years. In addition the deterioration would limit the future utility of the presently uncommitted yield from Wellington Reservoir. Following consideration of a number of options, reforestation of cleared farmland in the drier, high salt-yielding parts of the catchment was commenced in 1979/80.

The reforestation programme was initially proposed to run for six to ten years with an annual replanting target of 2000 ha. The actual planting rate achieved has varied between 700 and 800 ha per year, with a total of 5737 ha having been reforested to the end of 1988. The areas planted have been concentrated in the eastern and south-eastern portion of the catchment where the annual rainfall is usually less than 750 mm per annum (Figure 32). The reforestation strategy involved planting along the valley floors and lower side-slopes, the remaining middle and upper slopes providing viable strips of cleared farmland which could then be exchanged for lower slope areas on adjacent farmland to further extend the area of reforestation.

In 1985 the reforestation programme was reviewed as part of the environmental assessment for the Harris Dam Project and a target planting area of 8000 ha was established. This programme should exert control over salt discharge from 18500 hectares of the 51 000 ha of cleared farmland in the high salt-susceptible zones of the catchment. At the current rate of 700 to 800 ha/yr the programme should achieve 8000 ha by the early 1990s.

With the current planting rate and present knowledge of groundwater responses to reforestation, inflow salinities to Wellington Reservoir are not expected to reduce until the middle to late 1990s. Figure 33 shows the estimated effect of the current reforestation programme on inflow salinities in a year of median inflow. Two levels of control over saline discharge have been assumed. If the programme is moderately effective (reducing groundwater discharge by 50%) then average inflow salinities are likely to peak in the mid-1990s and return to about 1000 mg/L by the year 2010. This is similar to the current estimated average inflow salinity. If the reforestation is 100% effective and reduces groundwater discharge to zero, then it is predicted that salinities could be returned to 850 mg/L TSS by 2010. Much higher salinities will of course occur in drought years.

5. *Agricultural Strategies*

5.1 Introduction

The potential to manipulate the water balance of catchments by altering agronomic practices on farmland in the south-west of Western Australia has been discussed by several authors (Anderson, 1980; Sedgley *et al.*, 1981; Nulsen and Baxter, 1982; Nulsen, 1984; Greenwood *et al.*, 1985). Common to all of these papers is that different agronomic practices should result in different amounts of water being removed from the landscape via evapotranspiration. This evidence has led to speculation that altering agronomic practices on entire catchments, or parts of catchments, will lead to changed recharge rates, and consequently, a reduction in areas of salt-affected land and stream salinities. However, the relationship between agronomic practice and stream salinity has not been experimentally determined for any catchment within Western Australia and is likely to be catchment-specific. The gathering of experimental data on rates of evapotranspiration from different crops and pastures, combined with a better understanding of catchment hydrology using geophysical techniques (Engel *et al.*, 1989), will enable more successful management prescriptions to control salinity.

Control of saline seepage has been achieved in the Great Plains of North America by altering agronomic practice (Halvorson and Reule, 1976; Lilley 1982). Success resulted from abandoning summer fallow and by planting lucerne, or by increasing cropping frequency with high water using crops. Unconfined aquifers, deep fertile soils and localised groundwater flows make reclamation of saline seeps on the Great Plains relatively simple. However, farmer adoption of well researched reclamation techniques has so far been low. Lilley (1982) states: 'For most farmers, dryland salinity has only a minor impact on income and the farming operation, and seeps have become an accepted part of the farm environment'. This argument is likely to hold true for many farmers in the catchment areas of the major potable water resources in the south-west of Western Australia. Therefore, Lilley's conclusion that 'a co-ordinated, well planned effort by Government appears to be required in order to bring about any significant, rapid control of dryland salinity' is appropriate. Only if alternative crops or pastures capable of greater water use are heavily economically favoured is increasing stream salinity likely to be controlled without Government effort. Even under economically favourable circumstances, farmers may fail to adopt practices beneficial to stream salinity (Dumsday *et al.*, 1985).

Research into agronomic options in Western Australia has concentrated on measuring the evapotranspiration component of the water balance. In terms of the effect of agronomic manipulation upon stream salinity several assumptions have been adopted in this approach:

(a) increased evapotranspiration is directly equated to decreased recharge to groundwater systems;

(b) in turn, decreased accessions to groundwater lead to less saline seepage and lower stream salinities.

5.2 Pasture Species

Estimates of annual average recharge under different agronomic systems are presented in Table 13. The high annual recharge of subterranean clover-based pasture compared to lupins, wheat and barley was reported by Nulsen (1984) for Cunderdin and Kondut (both approximately 350 mm average annual rainfall). Hamblin and Poole (unpublished data) estimated recharge under subterranean clover, bare fallow and wheat at Wongan Hills (average annual rainfall 393 mm). Oram and Cooke (1982) estimated recharge beneath annual, perennial and lucerne pastures at Axe Creek, Victoria (average annual rainfall 650 mm). At a site with deep sands near Perth, Carbon *et al.* (1982) found that, in a year of 800 mm rainfall, a perennial grass pasture and native woodland had similar recharge rates, while recharge under clover was significantly higher. Under similar climatic conditions in Spain, Joffre *et al.* (1988) also found that recharge under perennial pasture was significantly less than under annual pasture.

These authors used different methods to arrive at their estimates and therefore comparison between authors may not be valid. Also much of the difference between estimated recharge beneath the same species is due to variations in seasonal rainfall quantity and distribution. However, common to all of these results is the relatively low water use of clover-based annual pasture and, consequently, high rates of groundwater recharge beneath it.

Table 13: Estimated annual average recharge under different agronomic systems

Treatment	Annual recharge (mm)	Site
Clover	162	Cunderdin
Lupins	61	Cunderdin
Wheat	139	Cunderdin
Barley	83	Cunderdin
Clover	125	Kondut
Lupins	80	Kondut
Wheat	47	Kondut
Barley	9	Kondut
Clover	17	Wongan Hills
Bare-fallow	20	Wongan Hills
Wheat	9	Wongan Hills
Annual pasture	50	Axe Creek, Victoria
Lucerne	22	Axe Creek, Victoria
Perennial pasture	30	Axe Creek, Victoria
Clover	341	Perth
Perennial pasture	176	Perth

Table 14: Pasture species evapotranspiration at Bowelling (Summary of results from September to December 1986, Scott and Sudmeyer, 1986)

Species	Evapotranspiration (mm)	Max. rooting depth (cm)	Max. biomass dry weight (t/ha)	Time of max. biomass
Murex	138	115	2.0	November
Subterranean clover	132	65	1.9	November
Serradella	131	95	4.0	November
Control[1]	131	95	4.1	October

[1] The control plot was a mixed annual pasture regenerated from the previous year's pasture (mainly subterranean clover, brome grass, silver grass and cape weed).

Differences in the maximum rooting depth of plants give them access to different amounts of stored soil water. The shallow rooting depth of subterranean clover has been observed by Hamblin and Hamblin (1985) and Ozanne *et al.* (1965) and partially explains its low annual water use.

Biomass of pastures and crops have been equated with their water use by numerous authors dealing with many different species (see Tanner and Sinclair, 1983). The inherently lower biomass and continuous removal of biomass by grazing animals leads to a reduced surface area available for water loss in pastures. In addition, annual pastures only have the ability to use water during a short growing period when evaporative demand is low. Therefore extended growing season annual pasture species and, more importantly, perennial pasture species have the potential to use more water than conventional sub-clover pastures.

On the basis of this supposition a trial was begun at Bowelling (35 km east of Collie) in the Collie River catchment in 1986. The site has an average annual rainfall of about 750 mm, but received only 310 mm in the 1986 growing season. Small plots of several pasture and crop species were sown and the ventilated chamber technique was used to measure evapotranspiration.

The results (Table 14) show that the greater rooting depth of Murex, *Medicago murex*, allowed it to use marginally more water than the sub-clover, serradella or control plots. The absolute accuracy of the ventilated chamber results is doubtful but this should not affect their relative accuracy. Indeed, Greenwood *et al.* (1985) using the same technique measured annual pasture evapotranspiration of 390 mm at Bannister (a site receiving the same annual rainfall) some 100 km to the north of Bowelling.

Nulsen and Baxter (undated) measured the annual transpiration of lucerne (*cv. Trifecta*) compared to a long season wheat (*cv. Osprey*) at Gairdner

Table 15: Transpiration and integrated dry matter persistence of four lucerne cultivars for the period March to October 1985 (grown on deep sand at Gibson)

Cultivar	Transpiration (mm)	Dry matter production (tonne days)
Springfield	248	192
Siriver	286	234
Sheffield	277	196
Hunter River	230	150

Table 16: Distribution of rainfall and temperature for representative stations

Parameter	Collie	Mount Barker
Average annual rainfall (mm)	977	753
% of annual rainfall Nov–Mar	10	20
Number of days with maximum temperature >30°C Nov–Mar	61	31

River (average annual rainfall 450 mm) in 1984–85. In this experiment the lucerne transpired 433 mm which was more than the rainfall (384 mm)—giving an indication of its potential to reduce recharge. At this site lucerne transpired considerably more than wheat (231 mm). They also compared the annual transpiration of four lucerne cultivars at Gibson (Table 15). Differences are evident between the cultivars which can be partially explained by differences in biomass.

The apparent potential for successful recharge control using lucerne in the 600–900 mm/yr zone of the south-west may be limited by the more seasonal distribution of rainfall and temperature (Table 16). The extended drought period will test the adaptation of cultivars of perennial species to soil types within that area. It is important that this be thoroughly assessed to ensure maximum reduction of recharge rates. Results from a programme to assess perennial pastures would provide valuable information for any economically based model to assess the viability of such a change in farming systems.

In the near future evapotranspiration from plots of lucerne and phalaris will be measured, and compared to the annual pasture species. Previous work on perennial pasture grasses suggests that around 500 000 ha of land is suited to perennial grasses in areas with rainfall greater than 800 mm/yr (Biddiscombe *et al.*, 1982). This area is contained south of a line drawn from Margaret River to Mt Barker. This work also suggested that soil profile depth and texture was important in the survival and yield of the most promising species in areas with average annual rainfall down to 500 mm. If it is shown that the perennial pasture species (phalaris and lucerne) will use more water than annual species at Bowelling, it is suggested that more detailed agronomic studies on adaptation, productivity and persistence will provide valuable information on the agricultural and economic value of perennials within catchment areas.

This information would also provide the basis for deciding what would be necessary to encourage farmers to adopt pasture systems that reduce groundwater recharge.

No information is currently available on the effect of agroforestry regimes on perennial pasture. Climate modification favouring perennial pasture species under agroforestry could also be explored within a research programme on perennial pasture species.

Research in Victoria indicates that recharge reductions can be achieved using perennial pasture, and particularly lucerne (Oram and Cooke, 1982). The Government of Victoria (1987) through its 'Salt Action' strategy is providing technical and financial assistance to farmers to encourage the establishment of perennial pasture.

Brouwer and van de Graaff (1987) compared the effect of deep ripping in a texture contrast (duplex) soil under lucerne and phalaris pastures. They concluded that deep ripping may increase deep infiltration despite also increasing evapotranspiration. Increased surface infiltration was guided laterally through the subsoil to sites where preferential flow channels carried the water deeper into the profile. These effects were still quite marked two to three years after ripping.

5.3 Crop Species

Recharge reductions using crop species have been shown in the lower rainfall zone of the agricultural area by Nulsen (1984). Anderson (1980) showed that there was as much variation in water use within crop species using different sowing times as there was between species. Clearly time of sowing is important in maximising the water use and yield of a field crop. Hamblin and Poole (unpublished) suggest that early planting systems, early maturing varieties, split fertilizer application and a deep rooted cereal or legume crop every year would be capable of achieving a reduction in recharge of 10 to 50 mm in all years, except those with abnormal rainfall.

The water use of crops is also affected by nutrient status (Brown, 1971; French and Schultz, 1984a; and Halse *et al.*, 1969) and pest control (French and Schultz, 1984b). Optimum fertilizer application and improved pest control will improve the water use of a given species. In areas with greater than 500 mm average annual rainfall, the hydrological benefits of maximising production from crops are more pronounced because the difference between potential and actual yield for this area is very large (Anderson, 1985). Recent recognition

Table 17: Crop species evapotranspiration at Bowelling (from September to October 1986, Scott and Sudmeyer, 1986)

Species	Evapo-trans-piration (mm)	Grain yield (t/ha)	Max. rooting depth (m)	Max. biomass (t/ha)	Time of maximum biomass
Lupins	214	1.7	-	11.0	December
Oats	197	2.5	1.15	9.3	November
Barley	173	2.8	1.1	10.1	October
Annual pasture	131		0.9	4.1	October

of the detrimental effects of waterlogging on crop production (Negus, 1983) and the likely role of perched water tables in groundwater recharge (McFarlane pers. comm.) point to improved crop production potential for some higher rainfall sites (see section 5.4).

The encouraging results from experiments in lower rainfall areas led to the inclusion of evapotranspiration measurements on crops at Bowelling in the Collie River catchment. Results from 1986 confirm the potential for recharge reduction using crop species (Table 17).

The 1986 results show that all crop species used more water than annual pasture. The differences in biomass production, rooting depth and the time of maximum biomass help explain the apparent differences in evapotranspiration. There is some concern that in a year with higher winter rainfall, the susceptibility of lupins to waterlogging and subsequent disease problems would lead to lower annual evapotranspiration relative to oats. All species were grown according to district recommendations in order to maximise yields. There is likely to be further scope to manipulate evapotranspiration by changing times of sowing and fertilizer rates to further increase yields.

The trial continued in 1987 with rape included as an additional crop species. The approach being followed is to assess the relationship between biomass yield and evapotranspiration for each species. Several years data will be required to assess that the data are consistent regardless of environmental conditions.

Application of these results to biomass yields on other sites and soil types will allow prediction of the most suitable crop type in terms of water use for a given site.

5.4 Surface Drainage

Waterlogging has been identified as a significant factor in reducing crop yields in the agricultural areas of Western Australia. Negus (1983) has documented yield losses due to waterlogging at Narrogin, Bakers Hill, Mount Barker and Kondinin varying in severity from total crop failure to yield reductions of 400 kg/ha.

The main factors influencing waterlogging are rainfall, soil type and topographical position (McFarlane, 1985). In the simplest case, the likelihood of waterlogging can be related to total annual rainfall. Reeves (1984) showed that wheat yields decrease in areas of Western Australia with average annual rainfall exceeding about 500 mm. Similarly, Cox and Negus (1985) showed yield reductions with excessive rainfall in wheat, barley and oats. Their yield loss data can be transformed into approximate 'transpiration deficit' figures using water use efficiencies for grain production from available data (Table 18). It should be noted that the 'transpiration deficit'

Table 18: Water use efficiencies, yield losses and approximate transpiration deficits for wheat, barley and oats

	Wheat	Barley	Oats
Water use efficiency (kg/ha/mm of evapotranspiration)	10	16	13
Source	D. Tennant, pers. comm.	Scott—unpubl.	Scott—unpubl.
Narrogin Shire			
5-year average yield (1979-83)(t/ha)	1.32	1.29	1.33
Wet year yield 1983 (t/ha)	0.97	0.89	1.03
Yield reduction in wet year (t/ha)	0.35	0.40	0.30
Transpiration deficit in wet year (mm)	35	25	23
Cuballing Shire			
5-year average yield (1979-83)(t/ha)	1.34	1.30	1.31
Wet year yield 1983 (t/ha)	0.87	0.80	0.97
Yield reduction in wet year (t/ha)	0.47	0.50	0.34
Transpiration deficit in wet year (mm)	47	31	26

may be partially offset by higher rates of soil water evaporation from saturated and near saturated soil when there is little vegetative cover (Denmead, 1973). Although water use efficiencies may be changed by periods of water-logging, no data are available to confirm this. The fact that waterlogging leads to reduced growth rates (Trought and Drew, 1980) and subsequently reduced yields, and that biomass and transpiration are positively correlated, suggests the existence of a (seasonal) 'transpiration deficit' due to water-logging. There is variation amongst species in their tolerance to waterlogging, and it is likely that dicotyledons, due to their inability to produce aerenchyma tissue to supply oxygen to roots, are generally less tolerant of waterlogging than monocotyledons (Barrett-Lennard, pers. comm. 1988).

Aside from the yield and associated transpiration reduction caused by waterlogging, it is likely that the perched aquifers causing waterlogging contribute significant amounts of groundwater recharge via preferred pathways. Johnston (1987) demonstrated that a considerable amount of groundwater recharge occured by preferred water flow through the subsoil in the Darling Range. Observations at Hardies catchment near Narrogin suggest that preferred water flow is the most important recharge mechanism where perched water tables occur in the landscape (Engel *et al.*, 1989). This rapid recharge to groundwater leaves little opportunity for plants to transpire the water.

Cox (1988) showed that shallow interceptor drains on a grade are capable of removing large amounts of excess surface and shallow subsurface water while it is still relatively fresh (i.e. before it has recharged saline aquifers). Drains at Mount Barker removed as much as 39% of growing season rainfall, and an average of 18% over three years. Drains at Narrogin removed 7% of growing season rainfall and an average of 2% over three years. The drains reduced waterlogging up to 80 m downslope. Cox also showed a general correlation between drain spacing and oat yield at Mount Barker.

On appropriate sites, it is clear that drainage can reduce the amount of water available for recharge, and route fresh water to streams. Although successful drainage will be site-specific, there may be considerable yield benefits in cropping years. The effect of waterlogging on pasture production was the subject of an experiment by D. J. McFarlane (pers. comm. 1989) at a site near Narrogin. His results suggest that seasonal pasture production was not influenced by moderate waterlogging. Drainage, however, conferred an advantage to the farmer by an increase in pasture production during the critical winter period, but a reduced production during the 'spring flush' when pasture levels are high. Further research into the effects of waterlogging on pasture production and the economics of draining land in pasture production is required.

It is likely that the main benefit of improved drainage in terms of stream salinity is through reduced groundwater recharge. In one study in the eastern Collie River catchment (PWD, 1981) the maximum reduction in stream salinity from harvesting shallow throughflow was estimated to be 20%. The stream salinity would have remained in excess of 3000 mg/L TSS even though a 25% increase in streamflow was estimated. This was because over 90% of the salts in streamflow came from the deep groundwater system. Consequently, surface drainage would not be a sufficient strategy, by itself, to control stream salinity. However, when integrated with other groundwater recharge and discharge control measures, it has some potential to ameliorate stream salinity.

Drainage schemes which do not effectively discharge water, and soil conservation structures which purposely retain water, can increase groundwater recharge (McFarlane *et al.*, 1986) and hence increase stream salinity.

5.5 Fodder Crop Trees

Little work has been done on the potential of perennial fodder crop trees to reduce groundwater recharge. Being deeper rooted than pasture species and perennials, the argument favouring their use for recharge reduction, although largely theoretical, has a sound basis. Their access to water stored deep within the profile will allow the creation of a larger soil water deficit than shallower rooted species. In addition, it is likely that there will be a considerable rainfall interception loss via the large leaf area of the canopy. However, the fact that the economic benefit of fodder crop trees is reliant upon periodic defoliation may limit the effectiveness of the trees in reducing groundwater recharge. In *Eucalyptus camaldulensis* seedlings, recovery after coppicing initially decreased water use, but after eight weeks, water use of the coppiced plants was greater than the untreated plants (Blake, 1980). The experiment was discontinued after eleven weeks. Similar effects on water use are possible in fodder crop trees, but there are no data on the effect of different defoliation strategies on water use.

In Western Australia there has been no comprehensive screening programme to determine species adaptation to sites, climate and management strategies. Although individual farmers have experimented with different species, tagasaste (*Chamaecytisus proliferus*) is well adapted to many soil types in the medium and high rainfall zones of the south-west of Western Australia (Negus, 1988). It has been observed to fail, however, in waterlogged and/or saline soils, and very heavy soils (D. Bicknell, pers. comm. 1989).

The Department of Agriculture has carried out trials on tagasaste at Bokerup (70 km east of Manjimup, average annual rainfall 650 mm) and at Bowelling (35 km east of Collie, average annual rainfall 690 mm). Both sites normally grow very good quality annual pastures on gravelly loam and sandy loam over clay soils. Neither trial has been able to show a net benefit to sheep in terms of body weight or wool production compared to annual pasture alone (Western Australian Department of Agriculture, undated; K. Hawley, pers. comm. 1988). Therefore, where good quality annual pasture is growing on good soil types one cannot confidently expect increases in sheep body weights or wool production (Negus, 1988). However, research into the benefits of tagasaste conducted by the Martindale Research Project has shown considerable increases in productivity can be achieved where tagasaste is grown on deep sands that normally produce poor annual pastures. Oldham and Mattinson (1988) have estimated that productivity on these soil types can be increased five-fold by providing tagasaste to pregnant/lactating ewes and young sheep in summer and autumn, thus replacing grain feeding. Snook (1987) has strongly recommended tagasaste as a high production fodder crop.

Further research is required on the benefits of grazing fresh tagasaste, of cut and carry systems, different management strategies, plant variation and density and designs of plantations on different soil types. Several innovative farmers are pursuing the use of tagasaste on deep sands, and the Martindale Research Project is providing information on the benefits of growing tagasaste.

Results from ventilated chamber measurements of evapotranspiration from tagasaste measured at Bowelling, in the Collie River catchment, showed that two to three year-old tagasaste (uncut, fenced, density = 600 stems/ha) used 400 mm per year (R. Engel and P. Scott, unpublished data). The results showed that transpiration rates were reduced substantially by stomatal closure from December until at least February. Under farm management conditions, however, it is likely that the trees would have been coppiced before reaching this age and the effect of this on water use is unknown. Until management systems for tagasaste plantations are better defined it is difficult to quantify its effect on recharge rates.

At Bokerup, tagasaste (planted at 1000 stems/ha) has lowered water tables by about 200 mm compared to annual pasture where there is no inflow of groundwater from outside the trial area. In other areas of the trial the tagasaste has not lowered water tables, apparently because of groundwater inflow from outside the trial (P. Scott unpublished data). It should be noted that the trees were considered to be too large for any effective management system and were consequently likely to have transpired more water than would be normal under a productive system. This result does suggest, however, that whole catchment treatments using tagasaste on suitable soil types could have the ability to reduce groundwater recharge.

Other species of fodder trees that are well adapted to local conditions could have an effect on recharge rates depending on the management systems invoked. Introduced species which may have potential include:

Tree medic (*Medicago arborea*)
White Cedar (*Melia azedarach*)
Mesquite (*Prosopis* spp.)
Carob (*Ceratonia siliqua*)
Tree lupin (*Lupinus arborea*)
Poplar (*Populus* spp.)
Acacia leucophloea
Willow (*Salix* spp.)
Honey locust (*Gleditsia triacanthos*)

In addition many native species are obviously well adapted but little is known about their grazing value, establishment, management or water use. These include: *Acacia saligna, Acacia blakeii, Bossiaea linophylla* and *Bossiaea ornata.*

5.6 Saltland Agronomy

Considerable research has been conducted on revegetating saline sites using halophytic (salt tolerant) vegetation. Most research on halophytic shrubs has been conducted in areas receiving less than 500 mm of rainfall annually, and therefore is not directly applicable to marginal catchments requiring active management to maintain water quality. Perennial grasses (*Paspalum vaginatum* and *Puccinellia ciliata*) may be used to revegetate some salt affected areas receiving more than 500 mm annual rainfall.

Saltland agronomy is confined in application to the groundwater discharge area. The main thrust of the saltland agronomy research conducted to date has been to produce fodder from saline sites, and establish vegetative cover to reduce soil erosion.

5.6.1 Salt-waterlogging interactions

The synergistic effects of salt and waterlogging were shown by Barrett-Lennard (1986) in a glasshouse experiment using wheat. He concluded that waterlogging substantially depressed wheat yields on soil containing moderate and low salt concentrations, whereas yields were only marginally depressed by the same salt concentration in a well drained soil. It is suggested that many other cereal and pasture plants are likely to be sensitive to waterlogging under low salt concentrations. These results demonstrate why the control of waterlogging on marginally saline land by interceptor or surface drains can substantially improve crop productivity (Barrett-Lennard, 1986). Waterlogging halts the growth of *Atriplex* spp. by preventing water uptake by roots. Plants may die if evaporative demand is high (Ali, 1988). Control of waterlogging is therefore important for growth of halophytic shrubs.

5.6.2 Establishment of halophytic vegetation

Runciman (1986) produced an excellent review of species choice and establishment techniques for revegetating saline sites with forage plants. Discussion was confined to grasses, forbs and shrubs including salt water couch (*Paspalum vaginatum*), puccinellia (*Puccinellia ciliata*), tall wheat grass (*Agropyron elongatum*), small leaved bluebush (*Maireana brevifolia*), samphires (*Halosarcia pergranulata* and *H. pterygosperma*) and numerous species of salt bush (*Atriplex* spp.). The following notes on suitable establishment techniques were adapted from Runciman's review.

Shrubs may be established in the field by transplanting seedlings or by direct seeding. Transplanting is a reliable method but is expensive and is better suited to experimental sites, small areas and areas of high priority (C. V. Malcolm, pers. comm., 1984)*. For most areas it is preferable to establish shrubs by direct seeding. In scald reclamation work, salt tolerant shrubs have been established by broadcasting seeds (fruits), either mechanically or by hand, on cultivated ground. However, a more precise method of sowing, which creates a micro-environment favourable for germination, has been developed by the Western Australian Department of Agriculture (Malcolm and Allen, 1981). This method is more successful for establishing *Atriplex* spp. and *Maireana* spp. on salt affected land (Malcolm *et al.*, 1980). Sowing is carried out with a seeder which constructs a raised bank, over which a press wheel is run to form a niche. *Atriplex* or *Maireana* seeds are deposited as spot placements at regular intervals along the niche. Above each seed placement, the machine automatically deposits a spot mulch of vermiculite followed by a covering spray of black latex paint. A number of mulches and sprays have been tested; vermiculite and black paint were found to give the best establishment for *Atriplex undulata, A. amnicola* and *Maireana brevifolia* (Malcolm and Swaan, 1985).

The furrow on either side of the raised bank catches fresh water which is stored in the subsoil close to the shrub thus aiding survival and growth. The bank raises the seed bed above ground level to overcome waterlogging and to help leach salt from the niche (Malcolm *et al.*, 1980). The vermiculite mulch reduces evaporation of moisture from around the seed bed, consequently minimising salt accumulation. The purpose of the black paint is to absorb radiant energy and transmit the heat to the seed; winter temperatures in the Western Autralian wheat-belt are probably not high enough for optimum germination of *Atriplex* species (Malcolm *et al.*, 1982; Laws, 1982). Black latex paint raises the temperature of the top 1–2 mm of soil by 5–10°C (Malcolm *et al.*, 1982; C. V. Malcolm and T. J. Doney, pers. comm., 1984); it also stabilizes the placement and reduces water loss. Alternative coatings may be used if a rise in temperature is not required. Adjustments are available for the spacing at which the bushes are sown and the number of seeds sown per placement; the optimum number of seeds to be sown per placement depends on seed fill, quality and viability.

5.6.3 Water use of halophytic vegetation

Little research has been conducted on the water use of halophytic vegetation. Greenwood and Beresford (1980) used the ventilated chamber technique to measure evapotranspiration from

* Research into planting bare-root seedlings of *Atriplex* spp using vegetable planting machines has recently commenced (C. V. Malcolm, pers. comm., 1988).

Atriplex vesicaria at Kellerberrin for two days in summer. Their results showed that evapotranspiration ranged from 1.3 to 3.3 mm/day. Transpiration from single plants was reduced at higher planting densities, but evapotranspiration from both plants and bare soil increased as planting density increased from 0.1 to 1.0 plants/m^2. Evaporation from bare soil, by contrast, was only 0.4 mm/day. A crude extrapolation of these figures suggests that the plants may have used about 250 mm of groundwater over the November to April period. Greenwood and Beresford (1980) also monitored water table levels beneath the plantation and concluded that *Atriplex* species *Atriplex vesicaria, A. rhagodioides, A. paludosa, A. undulata* and *A. bunburyana* were extracting groundwater from a water table about 1.2 m beneath the soil surface. The water table under plots with the closest spacing was 100–200 mm deeper than under the widest spacing. This suggests that *Atriplex* may have a hydrologic role in saltland reclamation in addition to its value as a grazing plant.

Sharma (1976) examined soil water regimes under *Atriplex vesicaria* and *nummularia* in the absence of a water table in sodic soils of Deniliquin, New South Wales. At this site (rainfall 378 and 365 mm in consecutive years) infiltration was insignificant beyond 300 mm in the soil profile. The root systems of the plants were correspondingly shallow and were able to extract soil water at very low potential values. Under the driest soil moisture conditions found in the study, *A. vesicaria* had shed 70% of its leaves, and *A. nummularia* 40%. Annual water use estimated from neutron probe measurements was, for *A. vesicaria,* 404 and 411 mm, and for *A. nummularia,* 401 and 411 mm for 1970 and 1971 respectively.

It is extremely difficult to extrapolate these water use results to the higher rainfall sites where different species are likely to be better adapted. Suffice to say that well established halophytic vegetation has the potential to lower water tables on saline sites. In particular, *Atriplex* species are well adapted to harsh sites where trees are difficult to establish, and provide the additional benefits of soil stabilization and fodder production. The major barrier to using *Atriplex* spp. in high rainfall (>500 mm) areas is likely to be winter waterlogging. A research programme on screening *Atriplex* spp. for waterlogging tolerance is about to commence in Western Australia.

6. *Integrated Catchment Management*

6.1 The Concept of Integrated Catchment Management

A strict definition of a 'catchment' has been given by Houghton and Charman (1986) as 'the area determined by topographic features within which rainfall will contribute to runoff at a particular point under consideration'. The size of a catchment ranges from a small hillslope or farm dam to a large river basin. For the purpose of catchment management, a catchment may be defined as 'the region upstream or downstream of a defined point for which disturbance to the hydrologic cycle will affect the quantity, quality and/or biological stability of its water resources'.

In Western Australia the Government is strongly committed to ensuring that the development of the State's economy does not undermine the quality of the environment. As a consequence the government recognised a need for a co-ordinated approach to catchment management and in 1987 adopted the policy of implementing an integrated catchment management (ICM) approach.

The objective of the State strategy for integrated catchment management is to achieve land and water allocation, use and management which are compatible in relation to long term community interests, resource suitabilities, reducing unwanted impacts of land and water use, and matters of equity and community values. The first application of the ICM approach to salt-affected catchments is to develop a plan for the Denmark River catchment, as discussed in the next section.

6.2 The Denmark Integrated Catchment Management Project

6.2.1 Background

The Denmark River Basin is a major potential water resource for the southern coastal region of south-west Western Australia. Currently less than 0.5 x $10^6 m^3$/yr is harnessed by a pipehead reservoir for water supply to the small town of Denmark. However, a major reservoir at the most likely site, near Mt Lindesay, has the potential to yield in excess of 25 x 10^6 m^3/yr (Stokes and Ruprecht, 1986). The significance of the Denmark River is that it is the only large potable water resource in the Albany region. Its loss as a utilisable water source would substantially add to the cost of meeting any major increase in the water demand of this region.

Average stream salinities (flow-weighted) were less than 600 mg/L TSS during the 1970s at the Mt Lindesay gauging station (just upstream of the pipehead dam) but they have increased to average 890 mg/L TSS over the period 1982–86. The annual maximum salinity averaged 3000 mg/L TSS during the 1982–86 period. While these recent high salinities are partly due to a sequence of very dry years, clearing of the native forest for agriculture has greatly increased stream salinity in this region.

Land clearing first took place in the 1860s in the Kompup catchment area. The first major clearing, however, occurred in the early 1920s when the Government Group Settlement Scheme was introduced. Subsequent major episodes of clearing occurred between 1946 and 1957, and between 1965 and 1973, coincident with improved prices for agricultural products, particularly beef. Large-scale clearing has ceased since 1979 when legislative controls on clearing were enacted.

By 1984, approximately 95 km^2 of the 525 km^2 of the catchment upstream of Mt. Lindesay gauging station were cleared. A large proportion (84%) of the cleared land is located within the low rainfall zone (700–900 mm/yr). Characteristics of the low rainfall zone are high soil salt storage and saline groundwater. Consequently, although this area currently produces only about 37% of the streamflow, it contributes about 72% of the stream salt load as measured at the Mt Lindesay gauging station. Stream salinities are expected to continue to increase for some years because of the delay between clearing and the full expression of groundwater salt discharge.

When the full effect of past clearing develops, it has been estimated that the annual stream salinity at the Mt Lindesay gauging station in a year of median streamflow would be about 725 mg/L TSS and in 10% of years (drought years) could exceed 1000 mg/L TSS (Ruprecht *et al.*, 1985). Construction of a major storage would dampen out some of the yearly quality fluctuations. However, supply quality would still exceed 675 mg/L TSS and 810 mg/L in 50% and 10% of years, respectively. Such levels will not be considered satisfactory for a major water supply scheme in the next century. A recent analysis of stream salinity trends (Steering Committee for Research in Land Use and Water Supply, 1988) indicates that stream salinities could rise significantly higher than the above predicted values.

6.2.2 The ICM approach to the Denmark catchment

Although agricultural development in the salt-prone upper Denmark catchment area is the major cause of increasing stream salinity, this area is also well suited for sheep and cattle grazing. The reliable 700 to 800 mm annual rainfall makes it a profitable agricultural region, although cost price pressures in recent years have emphasized the need for improved productivity. Production is currently based on annual pastures but there is considerable scope for the introduction of perennial pastures and cereal, legume and oil seed crops. In addition, significant areas of salinised and waterlogged soils exist and indicate that improved land management to ameliorate these problems would be highly desirable from a soil conservation as well as a catchment water quality perspective.

There is also a potential for the establishment of softwood and hardwood forestry. The catchment is close to Albany which is projected to develop into a forest industry regional centre. Softwood plantations are being established near Albany and a small mill-residue chipwood export operation has commenced. Both softwood and hardwood forestry could grow substantially in this region.

To maximise the long term value of forestry, agriculture and water resources in the region, it was considered appropriate to undertake an integrated catchment management approach to the Denmark catchment. A proposal was prepared and subsequently approved by the State Cabinet in June 1987. The project is administered jointly by the Water Authority, the Department of Agriculture, and the Department of Conservation and Land Management in consultation with the local soil conservation groups. Funding is by State Government agencies with assistance from the Commonwealth through the National Soil Conservation Programme, National Afforestation Programme, and the Federal Water Resources Assistance Programme.

The project aims to develop an integrated catchment strategy to enhance farm productivity and profitability, and to improve the water quality of the Denmark River. It aims to reduce the salinity of water supplied from a large storage to under 500 mg/L TSS for 90% of the time. To reach this target, salt discharge from the groundwater system in the upper reaches of the catchment will have to be reduced by about 65%.

A range of different strategies to reduce saline groundwater discharge is being considered. There is scope to reduce both groundwater recharge and discharge over most of the cleared land. Agronomic methods such as more intensive cropping and planting perennial grasses, drainage works to reduce waterlogging, and the introduction of tree crops which have high economic return, could each have an important role in reducing groundwater recharge. The planting of some non-commercial, salt/waterlogging tolerant tree species in saline valleys is also seen as an important part of the salinity control measures.

As part of the catchment management strategy it will be necessary to involve all land owners in the upper catchment area. Preparations are under way to establish three experimental sites in the upper Denmark and upper Hay catchments. On one site commercial trees will be planted over a large proportion of the sub-catchment. The economics of this strategy will be evaluated in terms of returns from wood and agricultural production and improved water quality. Another site will be used to study the effect of local drainage improvement together with the introduction of intensive cropping and perennial grasses. Salt/waterlogging tolerant trees will be planted in the discharge zones on both sites. The third site will be a control.

The first three years of the project will involve a detailed land capability survey and production of a plan for integrated tree planting, drainage and agronomic management.

7. *Management Issues*

7.1 Role of Remnant Native Vegetation in Salinity Control

The two main forms of land tenure in the south-west region are freehold and Crown land. Table 19 gives the distribution of land by tenure and rainfall zone for the area from the Helena catchment in the north to the Hay catchment in the south, excluding the coastal plains.

Freehold land is predominantly cleared for agriculture. For four south coast shires the proportion ranges from 80 to 95% (Table 20). However, total freehold as a proportion of total land ranges from 15 to 67%, such that the uncleared part of freehold land as a proportion of total land ranges from only 2.8 to 6.0% (Table 20).

In the five clearing control catchments (Helena, Collie, Warren, Kent, Denmark) considerable areas of freehold land have been protected from large-scale clearing under the Country Areas Water Supply Act. All are in the intermediate and low rainfall zones (Table 21).

Table 19: Distribution of land (km²) by tenure and rainfall

Tenure	High rainfall zone (>1100 mm)	Intermediate rainfall zone (900–1100 mm)	Low rainfall zone (600–900 mm)
Freehold	1500	1800	9300
State Forest /Crown	9000	4000	4000

Table 21: Areas protected from large-scale clearing

Catchment	Total area (km²)	Freehold farmland (%)	Native vegetation controlled by Country Areas Water Supply Act (%)	Existing State Forest/ Crown land (%)
Helena	1470	2.5	2.5	95
Collie	2830	23.0	12.0	65
Warren	3890	32.0	14.0	54
Kent	1650	40.0	15.0	45
Denmark	650	16.0	5.0	79

The clearing of further land for agriculture is also constrained by the Soil and Land Conservation Act, under which notifications of intent to clear are evaluated for their likely soil conservation (including salinity) consequences. Operation of this Act is currently being reviewed due to recommendations arising from the Environmental Protection Authority's (EPA) recent assessment of the proposal to extend the licence for woodchipping in the southern forest (EPA, 1988; WA Chip and Pulp Co. Pty. Ltd., 1987). The EPA was concerned about the biological conservation value of remnant native vegetation on farms and the possible acceleration of clearing if woodchipping was available to help fund clearing operations.

Table 20: Areas and percentages of Crown, freehold, freehold remnants and freehold cleared lands for four south coast shires

Shire	Total area	Crown as percent of total area	Freehold as percent of total area	Freehold remnants as			Freehold cleared farmland as	
	(km²)	(%)	(%)	% total	% freehold	% Crown	% total	% freehold
Albany	4458	38.7	61.3	6.0	9.8	13.4	55.3	90.2
Plantagenet	4827	32.8	67.2	3.4	5.0	9.4	63.8	95.0
Denmark	1843	71.7	28.3	4.5	15.8	5.9	23.8	84.2
Manjimup	6894	84.7	15.3	2.8	18.5	3.2	12.5	81.5

Although remnant vegetation on farms is only a small proportion of total land under native vegetation (3–13%, Table 20), it is nevertheless an important component of integrated management to achieve salinity control. In the high rainfall zone and the less salt sensitive parts of the intermediate rainfall zone, further clearing, or forestry management involving thinning (Steering Committee for Research on Land Use and Water Supply, 1987), would increase fresh water yield. In the saline parts of the intermediate rainfall zone and the low rainfall zone, further clearing would increase stream salinity. There is a need for the State to develop policies which will facilitate an efficient contribution to integrated catchment management from remnant native vegetation. Such policies will need to address all aspects of the remnant vegetation question, including the property rights of the owners, biological conservation values and soil conservation and salinity values.

Until recently little detailed information was available to guide integrated management. In particular, data on the biological conservation value, potential for forestry production, current condition, size and distribution of remnants were lacking. This deficiency was highlighted by the controversy concerning the area of remnants available to sustain a farm-based woodchipping proposal in the Denmark district (McLean Sawmills, 1986; EPA, 1987).

The Department of Agriculture is currently developing an inventory of the size, perimeter and

Table 22: Area, perimeter and frequency of occurrence of remnant vegetation stands in five area categories for four south coast shires (Data provided by G. Beeston pers. comm. 1989)

SHIRE	Area category	Total area		Total perimeter		Total frequency	
	(ha)	(ha)	(%)	(km)	(%)	(No.)	(%)
Albany	1–10	270	1	43	3	36	14
	11–50	3600	13	344	28	145	57
	51–100	2300	9	158	13	33	13
	101–500	6800	25	337	27	30	12
	>501	13700	52	353	29	11	4
		26670		**1235**		**255**	
Plantagenet	1–10	400	3	68	7	58	20
	11–50	3450	21	354	37	151	53
	51–100	2800	17	194	20	41	15
	101–500	6050	37	250	26	31	11
	>501	3600	22	89	10	4	1
		16300		**955**		**285**	
Denmark	1–10	100	1	17	4	16	16
	11–50	1290	16	125	27	51	50
	51–100	1200	15	79	17	17	16
	101–500	3730	45	175	38	18	17
	>501	1930	23	66	14	1	1
		8250		**462**		**103**	
Manjimup	1–10	980	5	210	14	232	46
	11–50	4610	23	492	33	185	37
	51–100	2590	13	184	12	38	8
	101–500	8600	44	452	31	41	8
	>501	3040	15	150	10	5	1
		19820		**1488**		**501**	

location of all occurrences of remnants greater than one ha in area throughout the south-west (G. Beeston pers. comm. 1989). Some of this data is shown in Table 22. This Table shows the details of remnants in five area categories for four south coast shires from Manjimup to Albany. It can be seen that the large size categories (greater than 100 ha) contain 60–80% of the total area, 40–50% of the perimeter, but have only 10–20% of the frequency of occurrence. In contrast the small size categories (less than 50 ha) have only 15–30% of the area, 30–50% of the perimeter but 70–80% of the frequency. These data indicate that any effort to upgrade the management of remnant vegetation would be most efficiently focused on the large area categories.

This area inventory needs to be augmented by data on the biological conservation value, forestry production potential and current condition of the forest. General observations indicate that much of it has been heavily exploited for timber but rarely given adequate regeneration or silvicultural treatment. Small dispersed areas, in particular, are exposed to grazing, fertilization, weed invasion, insect and disease attack, and in lower topographic areas, to groundwater inundation and salinity. Understorey is often absent and regeneration of overstorey prevented due to grazing. Much of this vegetation is badly degraded and many types are suffering high mortality.

There is an urgent need to establish a rational basis for the management of remnant vegetation on farms. This will require the following:

- Expansion of existing geographic information systems to incorporate all attributes of land carrying remnant vegetation. This will provide a data base to assist in the assessment of land clearing applications, to help develop management priorities for remnants and to monitor the change in remnants over time.
- Development of a procedure to identify and rank biological conservation values of remnant vegetation both on the basis of intrinsic merit and as part of a local conservation network.
- Development of procedures to encourage farmers to protect, manage and improve production from remnant vegetation. In particular to design these procedures to facilitate protection of areas with high biological conservation value.
- In the high rainfall zone, to develop criteria and procedures to guide the clearing or thinning of remnants where the fresh water yield and land production benefits exceed the biological and soil conservation values lost.
- In the low rainfall zone, to develop criteria and procedures which will make the clearing of remnants conditional on the implementation of other salinity control practices which will more than offset salinity loss due to clearing.
- In the intermediate rainfall zone, to develop the means to decide at a local scale whether the high rainfall zone or low rainfall zone practices for remnants should apply.

7.2 Ongoing Reforestation of Wellington Dam Catchment

The Water Authority is committed to the long term objective of returning the Collie River to a salinity level such that Wellington Reservoir is suitable for domestic water supplies. This commitment was given as a condition of environmental approval for the Harris River Dam Project and is a statutory obligation under the Environmental Protection Act 1986. Thus a long term programme of ongoing rehabilitation of Wellington Reservoir catchment will be required.

In additional the Minister for the Environment required the Water Authority to 'review current research projects and the existing catchment management programme, in particular the reforestation programme, with a view to:

- assessing the prospects for a range of alternative strategies, including tree farming, to control saline discharges from affected areas; and
- assessing possible time frames for implementing further catchment management options and redirecting research and development programmes as appropriate.'

The future reforestation programme will reflect many of the findings presented in this review and will follow a new management approach.

A significant limitation of the current reforestation programme has been the slow rate at which salinity control is brought about in practice. This is largely due to the time taken in purchasing land and planting trees. One consequence of this has been the need to construct another reservoir (Harris dam) on a fresh tributary in the catchment to supply the Great Southern Towns Water Supply Scheme. Thus there is a clear need in the future to plan catchment rehabilitation measures well in advance of water resource development needs.

7.3 Regional Location of Commercial Tree Plantations

The development of commercial tree plantations on farmland has the potential to both increase and decrease stream salinities. Recent studies have shown that dense plantations of pines can significantly reduce stream salt loads but they also reduce streamflow volumes substantially. When located in regions of high salt discharge they can significantly improve the salinities of regional water resources. If, however, they are planted in rainfall zones above 900 mm/yr, they are more likely to increase the salinity of regional water resources through reducing the dilution effect of streamflow from the high rainfall portions of these catchments. Means of directing commercial tree plantations into areas which have the most long term benefit to salinity control will be required.

7.4 An ICM Approach to Stream Salinity Rehabilitation and Farm Planning

Experience with the reforestation programme on the Wellington Dam catchment has emphasised that an integrated approach to farm and catchment planning, which seeks to maximise land productivity while also reducing stream salinity, is essential if large river systems are to be cost-effectively rehabilitated.

The subdivision of land associated with the Wellington reforestation programme took into consideration practical aspects of farm management such as access to water supplies, sheds and other services. The integration of commercial tree planting and new agronomic methods for the remaining agricultural land will necessitate a much higher level of farm and catchment restoration planning. The upper Denmark catchment project will clearly demonstrate the approach required.

8. *Future Research Requirements*

Research associated with vegetation strategies to ameliorate stream salinity problems has been pursued for about 14 years. While considerable progress has been made, many problems remain and other issues, particularly management issues, are just emerging.

Research in this field is generally long term, and existing programmes will need to be extended and expanded if there is to be success in reclaiming salt-degraded water resources. The following sections identify the major future research requirements.

8.1 Reforestation Strategies

(i) DEVELOPMENT OF THE COMMERCIAL VIABILITY OF PULPWOOD CROPS

The greater the commercial competitiveness of pulpwood crops, the greater will be the scope to achieve salinity benefits. Basic silvicultural practices for pulpwood cropping on farmland are available. These are adequate for initial operational plantings. However, a substantial research effort will be required to achieve the full potential of pulpwood crops both in direct on-farm production and downstream benefits. The Department of Conservation and Land Management has initiated a comprehensive research programme. This programme seeks to co-ordinate the range of inputs and interests amongst Government Departments and commercial bodies. The major concepts and objectives in this research are:

- *Site selection and growth prediction*

  Land available for planting must be assessed to estimate costs and yields. This will require a land classification system and the definition of land productivity classes. For each class a growth model incorporating management input options will predict yield. This will provide inputs for economic analysis and preparation of sharefarming contracts.

- *Establishment and management techniques*

  In a short rotation tree crop the slow establishment phase takes a relatively large proportion of the rotation length. This phase is very responsive to better establishment technique with large yield and economic benefits. Also over short rotation lengths larger input costs can be entertained as the return comes relatively early. Experiments are required to test the full range of establishment and management options over the range of sites. Factors which require testing include seedling type and quality, ectomycorrhizal inoculation, cultural preparation, weed control, time of planting, nutrition, stocking rate and insect control. Fire control is another management factor which will assume increasing importance as the age and density of plantings increase.

- *Genetic improvement*

  Initial plantings will rely on 'wild' seed. A large step-up in yield potential is available from genetically improved planting stock. It will take at least five years before a sufficient amount of improved seed is available from seed orchards for large scale planting. It is therefore a major objective to develop clonal propagation techniques to shorten this period. Automated micropropagation is the most promising technique. Breeding populations of *E. globulus* have been established and are being upgraded to include the full range of genetic diversity of the species. Elite stock is being selected for inclusion in production populations.

- *Other species*

  E. globulus is the species of choice due to its established reputation in the pulpwood industry and its adaptability, vigour and productivity on local sites. However other species may prove better on some sites. Prospective eucalypt species are being tested and subjected to genetic improvement programmes. *Acacia* species are also recognised pulpwood producers and being legumes may improve yields on less fertile sites.

- *Trees within farming systems*

  Bulk planting of pulpwood crops may be attractive to some land owners. However, a greater number of mainstream farmers could be attracted if the value of pulp crops as an integral part of farming systems could be developed and demonstrated. There is probably an optimum area, stocking rate (agroforestry), distribution and range of species of trees required as part of sustainable and productive farming systems. Such systems would exploit the considerable secondary benefits of trees which include not only the treatment of degraded land and water but also shade and shelter, erosion control, economic diversification and aesthetics.

- *Economic analysis*

  One of the major objectives of research is to improve the cost and yield data for the full range of sites and management options. Economic models are being developed to utilise this data in the analysis of cropping strategies and the determination of share-farming annuities. These models have been designed to permit any combination of farmer input to establishment and management costs and any proportion of farmer return taken as annuities or final harvest payout.

  The level of adoption of pulpwood crops on the basis of their on-farm commercial benefits may not always be sufficient to gain the salinity benefits required. Economic studies should be undertaken to evaluate the water resources value of salinity control so that policies can be formulated to encourage pulpwood crops.

(ii) UNRESOLVED ASPECTS OF EUCALYPT AGROFORESTRY

These include determining whether pruning would allow fungal disease to enter the tree; assessment of the observed inhibiting effect of some eucalypts on pasture growth; and determining the marketability of fast grown eucalypt sawlogs.

(iii) TREE ESTABLISHMENT ON SALT/ WATERLOGGING AFFECTED SITES

Saline seeps cover up to 20% of catchments cleared for agriculture. These areas will continue to be sources of stream salt unless they are successfully revegetated. Establishment of salt and waterlogging tolerant trees on saline seeps, in combination with revegetation upslope of seeps, would be the most satisfactory means of totally controlling salt discharge. It is important that the research programmes underway to select and breed trees for saline seeps and to develop appropriate establishment techniques continue.

Trees selected for salt/waterlogging tolerance in glasshouse trials should be tested in the field. Once a range of trees adapted to saline seep conditions are identified selection should be refined to include water use and secondary benefits.

For non-core areas of saline seeps it is possible to establish trees which will provide secondary benefits. For example, *E. camaldulensis* is a suitable pulpwood and timber species although it seems unlikely that the returns from wood alone would make it an economic crop to establish in saline seeps. There is a particular need to select and evaluate such multiple use trees for planting in non-core areas of saline seeps.

For core areas of saline seeps it may not be possible to select plants which provide substantial economic benefits but it may be possible to select for environmental and conservation benefits. The water use characteristics of adapted plants should be evaluated, in particular water use of *Casuarina obesa*. This species appears to be the most salt/ waterlogging tolerant of species tested to date, but there have been suggestions that it would use less water than broad-leaved plants such as some *Melaleuca* species.

Initial results from experiments in the Wellington Dam catchment to improve establishment techniques in saline seeps appear promising. However, further evaluation of these experiments is required. Any promising techniques should be evaluated in a range of (saline seep) conditions including hillside seeps as well as valley bottom seeps, and in other catchments which may require reforestation.

(iv) EFFECT OF SALT ACCUMULATION BENEATH REFORESTATION

Reforestation of land on or near saline seeps may raise the salt concentration in the unsaturated zone and groundwater. Evidence from studies reported here indicates that groundwater salinity has decreased under both pasture and reforestation at sites with ~700 mm/yr rainfall but increased at a site with ~500 mm/yr rainfall. Salt concentration in the unsaturated zone beneath reforestation has increased at one of two sites where the measurement has been made. At the other site soil salt content decreased from 0–0.75 m and increased from 0.75–2.25 m. There is no documented evidence of loss of tree vigour where salinities have increased in these studies. Where groundwater level has lowered there is evidence that surface soil salinity has decreased. Moreover, if the water table is lowered, waterlogging will be reduced. Plants have a much greater tolerance of soil salinity under aerobic as opposed to anaerobic (waterlogged) conditions.

Further research on salt dynamics beneath reforestation stands is appropriate where any doubt exists on the long term viability of reforestation. This is particularly the case where discharge zone and near-discharge zone plantings are emphasised.

(v) MANAGEMENT OF REMNANT NATIVE FOREST

There is an urgent need to establish a rational basis for the management of remnant vegetation on farms. This should address the questions of what are, and how to protect the biological conservation values of remnants. With regard to soil conservation and stream salinity, the criteria and procedures to guide clearing or protection and management of remnants must be upgraded.

8.2 Agricultural Strategies

(i) ESTABLISH THE VALUE OF PERENNIAL PASTURES WITH PARTICULAR REFERENCE TO LUCERNE

In addition to the evapotranspiration studies of lucerne and phalaris plots in the Collie catchment, the following research on perennial pastures is required:

- evaluate species/variety adaptations to soil types and landscape position;
- determine and demonstrate the grazing value of perennial pasture, and assess its role within the farming system by economic analysis;
- investigate potential problems with *Rhizobium* inoculation and aluminium toxicity;
- determine the impact of perennial pastures on groundwater recharge.

(ii) ESTABLISH A FODDER SHRUB SCREENING PROGRAMME

Although there is a sound theoretical basis for assuming that recharge beneath fodder shrubs will be significantly less than beneath annual pasture, the agricultural potential of these species is largely unknown. The following aspects require research:

- adaptation of species to soil and sites;
- grazing value of a range of fodder shrubs;
- management techniques for fodder shrubs.

(iii) GRAZING POTENTIAL OF ANNUAL AND PERENNIAL PASTURES UNDER AGROFORESTRY SYSTEMS

Although considerable research has been devoted to timber production and groundwater responses under wide-spaced agroforestry systems, insufficient attention has been given to agricultural production in these systems.

The following research is required:

. investigate animal production from annual and perennial pastures under different agroforestry regimes;

. determine the possible benefit of trees on perennial pasture performance;

. analyse economics of grazing under agroforestry.

(iv) ASSESS THE ROLE OF SHALLOW SURFACE DRAINS ON WATERLOGGED LAND

Preliminary research has shown that surface drainage which promptly moves water to a flowing stream has potential to reduce groundwater recharge and increase fresh streamflow. At the same time drainage schemes have been shown to improve plant production, particularly in very wet years. Further research should include:

- measurement of plant production of annual and perennial pastures on drained and undrained sites;
- quantification of the effectiveness of surface drains in reducing groundwater recharge and increasing fresh water contributions to streamflow;
- demonstration of drainage techniques on appropriate sites, clearly conveying the correct design of drains (poorly designed/ constructed drains can increase groundwater recharge and stream salinity).

8.3 Hydrological Research

(i) STREAM AND GROUNDWATER MONITORING PROGRAMMES

Evaluation of the effects of rehabilitation methods is a long-term process. Although many results have been presented in this report, ongoing monitoring is required. This is the case for both groundwater and surface water monitoring of the effects of reforestation strategies. The oldest sites have only been monitored for a 10 year period and some sites still have insufficient data to draw preliminary conclusions. In particular further direct measurement is required of the effectiveness of partial reforestation in combination with agricultural strategies in reducing salt export and stream salinity.

Currently little monitoring has been carried out on the effects of upslope recharge control strategies. There is a need to establish long-term monitoring of the effects of agricultural and agroforestry strategies which cover a high proportion of the whole landscape. The establishment of further long-term surface and groundwater monitoring sites are likely to be expensive but are considered very cost-effective.

Further evaluation of the difference between groundwater recharge control using low and moderate density agroforestry stands is required particularly if agroforestry is to be promoted for salinity control purposes.

(ii) TREE WATER USE

While emphasis has been placed on selecting species based on site adaptation or commercial viability, improved knowledge of transpiration characteristics and possible reasons for site adaptation behaviour is required. This is necessary to improve modelling of the areas required for reforestation and to improve the confidence in species selection. This may necessitate development of improved research techniques so that continuous annual estimates of tree transpiration can be reliably obtained. Such work will be difficult but should be addressed.

(iii) IDENTIFICATION OF PREFERENTIAL RECHARGE AREAS

An optimal design in revegetation planning would take account of any preferential recharge areas within a catchment. Although research to date has shown that recharge rates are highly variable at a small scale (~ several metres), preliminary investigations indicate that systematic broad scale variations in recharge occur in eastern, lower rainfall areas. The following research needs have been identified:

- to investigate the broad-scale use of electromagnetic induction (EM) surveys to identify areas of low salt storage (which are usually areas of high recharge);
- to identify and determine the importance of dolerite dykes in saline seep development;
- to assess the importance of preferred pathway recharge in duplex soils.

(iv) PREDICTIONS OF THE EFFECTIVENESS OF VEGETATION STRATEGIES IN CONTROLLING STREAM SALINITY

A model to predict the future stream salinity and water yield of Wellington Dam catchment following partial reforestation was developed in the late 1970s. There is a need now to upgrade this model to give improved future predictions, to discriminate between different vegetation strategies and to be applicable to a number of catchments. The model should be able to take account of new research data as it becomes available. It would also be a valuable tool in catchment management planning for salinity control.

9. *Conclusions*

9.1 Reforestation Strategies

- A number of reforestation strategies, including lower slope and discharge zone planting, wide-spaced plantations and extensive dense plantations have lowered groundwater tables beneath reforestation relative to the ground surface over the period from planting in 1978/79 to 1986.
- Groundwater levels beneath pasture have risen relative to the ground surface over the experimental period.
- All reforestation strategies have lowered groundwater levels beneath reforestation relative to groundwater levels beneath pasture. However reforestation strategies involving planting less than 15% of the cleared land have not generally lowered groundwater levels beneath reforestation relative to the ground surface, over the experimental period.
- The experimental period was characterized by rainfall 10% less than the long term average. Under long term average rainfall conditions, it is probable that areas of reforestation of order 50% would be required to achieve any lowering of the groundwater level beneath reforestation relative to the ground surface.
- The rate of groundwater level reduction beneath reforestation relative to that beneath pasture was found to be proportional to the product of proportion of area planted and crown cover. Thus total crown cover rather than reforestation strategy appears to be the main factor in controlling groundwater level.
- A component of lower slope and seep area reforestation in the vegetation strategy is necessary if all salt discharge via groundwater is to be eliminated.
- Species selection should be based firstly on adaptability to the site conditions. For a given set of site conditions a group of species (or provenances) would be adapted. Within such a group, species should be selected primarily on their commercial value. Annual water use by trees could also be a significant selection criterion if better data on this characteristic became available.
- Extensive dense plantations have been shown to dramatically reduce stream salt discharge from a small catchment in the 800–900 mm/yr rainfall zone. The streamflow was also reduced, to the extent that no stream salinity improvement occurred. Such reforestation of the low rainfall, high salt discharge parts of major water resource catchments would significantly improve the stream salinity of the whole resource.
- Good growth performance has been achieved by *E. globulus, E. saligna, E. botryoides, E. viminalis, P. radiata* and *P. pinaster* on well drained soils in the Wellington Dam catchment plantings including Stene's Arboretum.
- Early concern that the long term survival of reforestation would be adversely affected by increasing soil and groundwater salinity has not materialised to date. Groundwater salinity has decreased under reforestation at a number of sites where rainfall exceeds 700 mm/yr but has increased at one site where rainfall is 500 mm/yr. Unsaturated zone salt content has increased under reforestation at one of the two sites where measured.

9.2 Agricultural Strategies

- Lupins, oats, barley and lucerne transpire more water annually than do the widely used annual clover-based pastures. The relatively low water use by annual pastures is related to their shallow rooting depth, short growing period and heavy grazing. More hydrologic and agronomic studies on the potential of the perennial pasture species phalaris and lucerne are required.
- Shallow interceptor drains correctly designed and constructed are capable of removing significant amounts of fresh surface and shallow subsurface water from agricultural land. This can reduce waterlogging and consequently increase crop yield, which in turn implies decreased groundwater recharge.
- Fodder crop trees have the potential to lower groundwater tables if planted over large areas of agricultural land. At present there is too little known about their grazing value, establishment, management and water use to make any recommendations for use in areas growing good quality annual pasture.
- Halophytic shrubs have the potential to lower water tables on saline seeps. *Atriplex* species

are well adapted to harsh, low rainfall sites and provide additional benefits of fodder production and soil stabilisation. In higher rainfall areas (>500 mm/yr) *Atriplex* species may be adversely affected by winter waterlogging.

9.3 Management and Research

- In the absence of clearing controls, the inflow salinity in a median flow year to Wellington Dam was predicted to exceed 1500 mg/L TSS by 2010. As a result of clearing controls the salinity would be reduced to 1150 mg/L TSS. Partial reforestation of agricultural areas, initiated in 1979/80, is predicted to further reduce inflow salinities to about 850 mg/L TSS by 2010 if it is 100% effective in eliminating groundwater discharge.
- Reforestation control measures for large water resource catchments is taking tens of years to be implemented and become fully effective under the present scheme of land purchase and planting. The promotion of commercially-driven pulpwood plantations could accelerate the implementation of reforestation programmes.
- Integrated catchment management, that is the integration of water and land management activities on a catchment with the purpose of solving a particular problem or set of problems, is seen as the best approach to future catchment rehabilitation.
- Specific management issues to be addressed are:

  —developing a role for remnant native vegetation on farms within the context of integrated catchment management while also addressing the question of biological conservation;

  —investigation of the potential impact and the recommendation of measures to control the escalating insect problem in the jarrah forest;

  —development of means of directing commercial tree planting into areas which have the greatest benefit to salinity control.
- Specific future research requirements are:

  —to clearly evaluate the effectiveness of combinations of reforestation and agricultural strategies in controlling stream salinity;

  —to develop the commercial competitiveness of pulpwood cropping both as extensive plantations and as an integrated part of farming systems;

  —to continue research into tree selection and establishment on salt/waterlogging affected sites;

  —with respect to eucalypt agroforestry, to determine whether pruning would allow fungal disease to enter the tree, to assess the potential inhibiting effects of the eucalypts on pasture growth, and to determine the marketability of fast-grown eucalypt sawlogs;

  —to establish the value of perennial pastures, especially lucerne;

  —to screen potential fodder crop trees;

  —to further assess the usefulness of controlling waterlogged land with shallow surface drains as a salinity control measure;

  —to investigate the feasibility of identifying broad scale variations in recharge and geological structures by electromagnetic methods;

  —to determine water use by tree species adapted to and planted in different conditions;

  —to develop the capacity to model the potential effectiveness of various vegetation strategies in controlling stream salinity;

  —to analyse the economics of land and water productivity for various scenarios of partial reforestation of agricultural land.

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Appendix A: Members of the Steering Committee for Research on Land Use and Water Supply

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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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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
Dr M. Sivapalan	University of Western Australia
Secretary	
Mr P. Jones	Department of Conservation and Land Management

Appendix B: ***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

Adaptation	Change in an organism as a result of exposure to certain environmental conditions which makes it react more effectively to these conditions.
Agroforestry	The simultaneous use of land for agriculture and forestry.
Agronomy	Science of soil management and crop production.
Alienation (of land)	The process of opening up Crown land for private ownership.
Anaerobic	Living in absence of free oxygen (gaseous or dissolved) or conditions where there is no free oxygen.
Annuity	A payment falling due in each year during a given period, the capital sum not being returnable.
Aquifer	A formation that contains sufficient permeable material to yield significant quantities of water.
Arboretum	A place devoted to the cultivation of a wide selection of trees for scientific or educational purposes.
Aerenchyma	Tissue with numerous large intercellular spaces. Aerenchyma may occur in the roots and stems of waterlogged plants where it facilitates oxygenation of the roots.
Biomass	Total quantity or weight of organisms in a given area.
Brackish water	Water with salinity greater than 1500 mg/L TSS *or* 600 mg/L chloride but less than 5000 mg/L TSS.
Canopy	The cover of branches and foliage formed by tree crowns.
Caprock	Usually refers to the lateritic duricrust, a hard layer formed in the upper part of the soil profile due to a concentration of aluminous and ferruginous materials drawn up in solution by capillarity.
Clone	A population of genetically identical individuals.
Coppice	1. The shoots or sprouts that develop on a stump following cutting. 2. The act of cutting trees to promote regeneration from stumps.
Crown cover	The vertical projection of tree crowns on the ground, usually expressed as a percentage of a specified area.
Crownometer	An instrument for measuring crown cover.
Culling	Removal of inferior or defective trees.
Cultivar	Variety produced by selection from cultivation.
Defoliation	The stripping or becoming stripped of leaves.
Dicotyledons	Members of the larger of the two classes into which flowering plants are divided. Includes woody plants and most herbs. So-called because of presence, on seedlings, of two (di) seedling leaves (cotyledons).
Discharge zone	The area of a catchment in which groundwater discharges to the ground surface.
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.
Duplex soil	A soil with a profile characterised by two texturally distinct horizons, the lower usually being finer textured.

Ephemeral	Lasting for a limited period of time.
Establishment of plants	Placing plants in conditions such that they are capable of normal growth and development.
Evapotranspiration	The loss of water from the land surface by evaporation from free water surfaces and soil and transpiration through vegetation.
Fallow	Land left unseeded after being cultivated.
Fauna	Animals of a region or period.
Fodder trees	Trees which are suitable for grazing or cropping for animal fodder.
Forb	Any herb other than grass.
Forest	Plant community in which the dominant plants are trees and crown cover is dense (>30%).
Genus	A group of similar species.
Germination	Emergence of shoot and root from a seed.
Groundwater	Water in the soil or subsoil of sufficient volumetric water content (usually saturated) to move in response to gravity and hydraulic pressure gradients.
Groundwater recharge	Water added to an aquifer from all sources.
Habitat	Place or environment in which specified organisms live.
Halophyte	Plant that is adapted to very salty soil.
Hydraulic head	The total head of a liquid at a given point.
Infiltration capacity	The maximum rate at which a given soil (in a specified condition) can absorb falling rain.
Integrated catchment management	The integration of water and land management activities and agencies to achieve the solution of particular catchment problems.
Interception	Water retained for some period, however short, after rain has struck the vegetation foliage above the mineral soil surface.
Isohyet	A line on a map joining places of equal rainfall amount.
Jarrah dieback	The progressive dying back of tree crowns as a result of the root rot fungus *Phytophthora cinnamomi.*
Land capability	Measures of land (particularly soil) characteristics which determine the capability of a site to sustain specific land uses.
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.
Leaf water potential	A measure of the free energy available to do work on water in a leaf.
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.
Monocotyledons	Members of the smaller of two classes into which flowering plants are divided. Includes grasses, many herbs and palms. So-called because of presence, on seedling, of one (mono) seedling leaf (cotyledon).
Mulch	Material, usually organic, such as cut grass, straw, foliage, sawdust, bark chips or woodchips used as a covering for the soil to conserve soil water and check weed growth.
Neutron moisture measurement	The measurement of soil water content by the neutron moisture meter method.

Pathogen	Infective agent which causes disease.
Perennial	Lasting through all seasons of the year or for many years.
Phreatophyte	Plant that is adapted to taking water directly from groundwater.
Physiological drought	A drought condition suffered by plants that occurs despite there being sufficient water in the soil. It may occur where the solute concentration in the soil water is equal to or greater than in the root cells so water cannot enter the plant by osmosis.
Pipehead dam	A small dam allowing a portion of the water flowing in a river to be diverted into a pipe.
Piezometric level	The level of water in a piezometer (bore) usually measured with respect to the Australian Height Datum (AHD)
Porometer	A small portable instrument for measuring leaf conductance.
Potable water	Water suitable for human consumption.
Potentiometric surface	The surface defined by water levels in a network of piezometers which are sunk into an aquifer.
Preferred pathways	Pathways such as root channels in which water can move rapidly through a soil without passing through the soil matrix.
Prescribed burning	The application of fire to land under such conditions of weather, soil water, time of day and other factors that will result in the controlled spread and intensity of heat required to accomplish specific silvicultural, environmental or fire hazard reduction objectives.
Provenance	The geographical source or place of origin of a given lot of seeds or plants. Within a species there are likely to be some genetic differences between provenances.
Pulpwood	Wood that is used to make paper pulp usually for further processing into paper.
Pump test	An aquifer test involving the measured discharge of water from a pumped well and the measurement of resulting changes in head in the aquifer, both during and after the discharge.
Recharge zone	The area of a catchment in which water is added to groundwater.
Regeneration (natural)	The renewal of a forest by self-sown seeds, advance growth or coppice.
Regolith	Mantle of more or less disintegrated material overlying the bedrock, together with superficial deposits of alluvium, drift, volcanic ash, loess, wind-blown sand and peat, including the soil layer.
Regression (line)	Line of best fit to data showing the relationship between two variables.
Rehabilitation	The return of a disturbed site to a less disturbed condition, usually meaning more productive and less degraded.
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.
Saline seep	Generally a wet, salty area due to a brackish or saline water table either at the land surface, or sufficiently near to allow significant capillary flow of water and salt to the land surface.
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.

Sawlog	A log that is to be sawn to produce timber.
Saturated hydraulic conductivity	The ability of a saturated porous medium to transmit water, defined as the rate of flow per unit cross-section area per unit hydraulic head.
Seep	A wet area due to a water table at the land surface or sufficiently near to allow significant capillary flow to the land surface.
Seismic survey	The investigation of underground structures by measuring ground movements following an artificial ground impact.
Semi-confined aquifer	An aquifer whose confining beds will conduct significant quantities of water into or out of the aquifer, according to the head distribution.
Solute	A substance which is dissolved in another.
Species	Generally a group of plants or animals that can breed amongst themselves to produce fertile offspring.
Statistical significance	The level of confidence, based on statistics, in a hypothesis. In general a level of significance of 5% in testing a hypothesis means that there are 5 chances in 100 that we would reject the hypothesis when it should be accepted.
Stem density	The number of (tree) stems per unit of ground area.
Stomatal conductance	The conductance to mass (water) transfer through the stomatal pathway of a leaf.
Storage coefficient	The volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head.
Subspecies	Sub-division of a species forming a group whose members resemble each other in certain characteristics, and differ from other members of the species, though there may be no sharp dividing line.
Surface runoff	That part of runoff which travels over the soil surface to the nearest stream channel, having not passed beneath the surface since precipitation.
Transpiration	The loss of water to the atmosphere from vegetation having been extracted from the soil by roots.
Unconfined aquifer	An aquifer overlain by permeable material and containing unconfined groundwater, that is having a water table and an unsaturated zone.
Unsaturated zone	The zone between the land surface and the water table, including the capillary fringe.
Vegetative propagation	Asexual reproduction whereby part of the parent is detached and forms a new individual.
Waterlogged	Anaerobic state due to saturation with water. Plants are generally considered to be subject to waterlogging if there is a permanent or temporary water table in the root zone.
Woodchip	Small piece of wood obtained from a log. Woodchips are used to make paper pulp, particle board and other products.
Woodland	Plant community in which the dominant plants are trees and crown cover is sparse (10–30%).
Woodlot	An area devoted to growing trees as a crop, usually on a farm.
Xylem	The tissues of the stem and root of flowering plants through which water passes on its way from the soil to the atmosphere.

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