Bauxite Mining in the Jarrah Forest

Impact and Rehabilitation

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Steering Committee for
Research on Land Use
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Acknowledgements

The Steering Committee for Research on Land Use and Water Supply extends its sincere thanks to the many people from various disciplines and organisations who through their dedicated efforts in data collection, analysis and interpretation have developed the body of knowledge on hydrology and forest ecology that is presented in this report.

The report was written for the Steering Committee by Dr N.J. Schofield (Public Works Department) and Mr J.R. Bartle (Forests Department) whose skills and application are gratefully acknowledged.

Foreword

Research programmes and investigations being carried out by staff of State Government Departments, Alcoa of Australia, CSIRO and Tertiary Institutions are continuing to improve our understanding of the impact of bauxite mining on the water resources and environment of the Darling Range. They are also guiding the development of improved rehabilitation and environmental management practices.

Although there is still much to be learned, there is now a good appreciation of the hydrology and forest ecosystem of the high rainfall region where mining is currently taking place. In addition, useful knowledge of the lower rainfall portion of the bauxite lease areas has been obtained from the general water resources assessment programme and from forest management and agricultural land use research studies.

In preparing this review, emphasis has been placed on the presentation of current knowledge together with an outline of research in progress and further work planned. This review is very timely. It marks the end of the first decade of research into the impacts of bauxite mining in the western zone of the forest, and sets the scene for a new period of co-ordinated research when the more difficult problems of mining in the eastern forest zone must be addressed.

M.J. Mulcahy
Chairman, Steering Committee for Research on Land Use and Water Supply

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Background

Bauxite mining began in the Darling Range in 1963 when Alcoa of Australia Limited opened its first mine near Jarrahdale. Since then the industry has expanded rapidly and in the early 1970s Alcoa opened additional mines at Del Park and Huntly. Their annual mining capacity is currently 13 million tonnes of bauxite which requires the clearing of 300 hectares of State Forest each year.

Two further mines have recently commenced operation — one at Willowdale (Alcoa) and the other at Mount Saddleback (Worsley Alumina). When fully developed these two mines could double present bauxite production and the rate of clearing of forest.

At the outset of bauxite mining, little concern was given to its potential impact on forestry and water resources. Only somewhat later, in 1973, was a Steering Committee formed to co-ordinate and supervise research into a number of emerging problems. Since that time, methods and procedures in bauxite mining and rehabilitation have advanced greatly, along with the increased understanding of jarrah forest ecology and hydrology. Now is an appropriate time to review the research, to re-assess the impact of bauxite mining and to determine the needs of future research.

Current mining and rehabilitation practices

Mining begins with the clearing of native forest on the prospective minepits and haul roads. The area of forest cleared is about 1.4 times that of the area to be mined and usually represents between 20% and 30% of the landscape. In the clearing operation, the commercial timber is logged and the remaining vegetation is bulldozed, stacked and burnt. The surface soil, which overlies the bauxite, is removed in two layers. The top 5 cm is transported directly to another area undergoing rehabilitation (if there is no risk of transferring dieback disease) while the remaining 35 cm or so is stockpiled. Research has shown that this double-stripping technique makes best use of the natural seed load of the topsoil and, in conjunction with supplementary seeding, produces a wide range of understorey species in the rehabilitated minepits.

Removing the topsoil exposes caprock, the upper cemented layer of the bauxite horizon. The caprock is drilled, blasted and then excavated along with the underlying friable bauxite, down to a depth of 4 or 5 metres. Excavation often proceeds as far as the underlying clay.

At the start of the rehabilitation phase, the compacted pit floor is ripped with a newly developed 'winged' tyne to a depth of about 1.5 metres. This procedure helps trees to establish roots in the clay and also improves water infiltration. The combined effect of removing vegetation and the more permeable surface soils has led to increased surface runoff. The resulting problems of soil erosion and surface water disposal are initially managed by the use of contour ripping, grade banks and artificial watercourses and sumps. Revegetation of the minepit further stabilizes the soil and increases water consumption, but several years may elapse before this is fully effective.

Trees are established from hand-planted nursery stock. The species are selected on the basis of their tolerance to dieback, fire and salinity; their timber quality; evapotranspirative potential; and aesthetic quality. The main currently used species in rehabilitation are *E. wandoo* (wandoo), *E. resinifera* (red mahogany) and *E. maculata* (spotted gum). Jarrah cannot be used as a major planted species due to its dieback susceptibility, although it is included in the understorey seed mix.

Impact of bauxite mining and rehabilitation

Bauxite mining is currently taking place in the high rainfall western zone of the jarrah forest. This zone is characterized by very low soil salt storage, low groundwater salinity and the most extensive deposits of bauxite ore.

The impact of mining and rehabilitation on water resources in the high rainfall zone (> 1100 mm) has been investigated by a triple catchment study over the last decade. From this study it has been concluded that, in the decade following mining, the catchment water yield increased by 20%-30%, the groundwater discharge increased in the same proportion as annual streamflow and the peak flows increased two to three times. The major part of the water yield increase came from near-surface lateral seepage. The concentration of salt in streamflow, however, remained unaffected, although the salt load increased in proportion to the yield. A separate groundwater study has shown that groundwater levels may rise by as much as two metres in six years following mining. Also, groundwater salinity may have increased slightly in mined areas as compared to forested areas. Further years of monitoring of rehabilitated catchments will be required before the long-term impact on the water resources of the high rainfall zone can be fully evaluated.

The impact of bauxite mining and rehabilitation on the forest ecology is less well documented. The performance of rehabilitation ecosystems prior to 1977 has generally been poor, both in terms of tree growth and faunal recolonization. Since 1977, improved nutrition, through increased application of fertilizer and the establishment of a legume understorey, has resulted in more vigorous and diverse plant communities. These have proved more attractive to fauna and are better able to sustain basic ecosystem processes such as nutrient cycling.

The creation of ecosystems on rehabilitated minepits requires the development of new management practices. These include new silvicultural and fire control methods, the possible continuing refertilization of rehabilitated areas, and the maintenance of drainage systems. These within-pit practices must be compatible with management of the forest at large.

Dieback disease

Mining can lead to the spread and intensification of jarrah dieback, a disease already widely established in the jarrah forest. No formal measurement of the advance of disease due to mining has been attempted. Instead, research has aimed at understanding the processes involved in disease development.

Mining operations and rehabilitation are now designed to reduce the potential for disease spread and intensification. This relies particularly on comprehensive hygiene practices and appropriate minesite water management. In addition, the Forest Improvement and Rehabilitation Scheme (FIRS) has been developed to rehabilitate old infected areas and to improve the resistance of healthy or lightly infected forest.

Future research needs

The major priority for future research is to evaluate the effect of extending mining to the intermediate rainfall zone (900-1100 mm) where there is a higher risk of increased stream salinity. Although mining is not expected to commence in this zone for some 30 years, and then only if proven safe, the problems are considered sufficiently serious and difficult to warrant immediate attention.

Planning for an expanded research programme in the intermediate zone is now well advanced. The programme will involve detailed ecological and hydrological monitoring and modelling at a number of experimental sites in the region. At one site it is currently planned to undertake 'trial mining and rehabilitation'. This will follow about 6 years of pre-treatment calibration. The mined ore will be stockpiled close to the trial mining location.

It is anticipated that modifications to current mining and rehabilitation methods will be necessary in the intermediate zone. To examine the scope and effects of a range of different methods, more detailed, process-oriented studies are required. These will be conducted mostly at the hillslope scale, which is sufficiently small to allow intensive instrumentation but, at the same time, adequately representative of processes to evaluate different mining and rehabilitation methods, both within minepits and downslope from them. Appropriate techniques and methodologies in this area are now being developed.

Conclusions

The environmental impact of bauxite mining and rehabilitation in the jarrah forest primarily involves water quantity and quality, the loss of native forest, and the introduction of new forest ecosystems by the rehabilitation of minepits and dieback degraded forest.

The major issue relating to water resources is salinity. In the undisturbed forest the stream water is of very low salinity and high quality. Bauxite mining in the high rainfall western zone of the forest (where mining will be confined for at least the next 30 years) has been shown not to significantly affect stream salinity because of the very low soil salt storage. Further east, however, the salt storage is much higher and may pose a major obstacle to mining. Research is now commencing to assess the effects of appropriate mining and rehabilitation practices in the intermediate zone. New methods to minimise salt leaching and discharge to streamwater will be developed and assessed. The success or otherwise of this work will have a strong bearing on the long-term future of bauxite mining in the jarrah forest.

The major issues in forest management are disease spread and the long-term stability and productivity of rehabilitation ecosystems. The greater understanding of the processes favouring dieback disease is leading to improved mining and rehabilitation practices. The stability and productivity of the pit ecosystems generated with the most recent rehabilitation methods appear to be well advanced over that of past methods. Attention has turned to the integration of rehabilitated forests with adjacent unmined forest to produce whole landscapes able to meet land use requirements.

Chapter 1

Introduction

Bauxite mining began in the northern jarrah forest at Jarrahdale in 1963. Expansion was rapid and by the late 1960s major new mines were planned in the Dwellingup area. Though environmental problems were initially considered to be minor, the rapid escalation of the scale of mining gave rise to increasing concern.

In response to the need to address the environmental issues raised by bauxite mining, the State Government in 1973 formed the Steering Committee on Research into the Effects of Bauxite Mining. The brief was to oversee a research programme with the following objectives:

(i) to establish whether bauxite mining could affect the water supply potential of northern jarrah forest catchments;

(ii) to investigate methods of revegetation.

Several research projects were formulated and each provided with a supervisory panel and working group. The broad representation of these groups also provided stimulation and co-ordination of related research. The Steering Committee progress reports (Department of Industrial Development, 1976, 1978) review this early work. They provide the first comprehensive definition of the environmental problems of bauxite mining, in particular the problem of salinity in the intermediate and low rainfall zone, and the potential increase in the size of the rehabilitation task by spread of disease during mining.

During 1978 plans to further expand bauxite mining and alumina refining were submitted to Government (Alcoa, 1978a; Worsley, 1978). This led to considerable public debate on the issue and an extensive environmental review of the expansion proposals (Technical Advisory Group, 1978; Environmental Protection Authority, 1978, 1979). As a result of this environmental review process, the need for joint planning of the mining operations between the State and the companies involved was highlighted and the need for broader based co-ordination of research programmes was recognised. Moreover Alcoa of Australia, as part of its revised Environmental Review and Management Programme, made the commitment that "*mining will not take place in the eastern, lower rainfall portion of Alcoa's lease, until research shows that mining operations can be conducted without significantly increasing the salinity of water resources*".

To rationalise the co-ordination of research into land use and water resource related issues, including bauxite mining, a Research Co-ordinating Committee was then established by the State Government. The Steering Committee for Research on Land Use and Water Supply was subsequently established to provide advice and guidance at the technical level. This new committee structure has superseded the previous Research Steering Committee.

This report by the Steering Committee for Research on Land Use and Water Supply describes in some detail the characteristics of the natural forest regime, identifies the potential for disturbance caused by mining and describes the approaches to rehabilitation which will moderate these disturbances. The report then describes the observed changes following bauxite mining and rehabilitation and discusses the implications for future land management and the priorities for future research.

The technical detail which forms the basis of this review has been drawn from the combined experience of numerous hydrologists, engineers, ecologists, geologists and foresters working on many aspects of the jarrah forest environment. While reference is made to many technical papers throughout the text the interested reader is specifically referred to two documents, one on hydrology (Loh *et al.*, 1984) and the other on forest ecology (Bartle, in prep) which provide a more detailed review of the technical information presented in this report.

Chapter 2
The Natural Forest Regime

To assess the effects of bauxite mining and rehabilitation on the jarrah forest it is necessary to have a close understanding of the undisturbed forest hydrology and ecology. Although the jarrah forest has in fact been partially disturbed by dieback, logging and other factors since European settlement, most of the forest still behaves as a natural system against which the disturbance of bauxite mining can be gauged. Research to date has encompassed many physical and biological aspects of the jarrah forest, both in relation to bauxite mining and other land use changes. This chapter summarises past research and presents a picture of our current understanding of the pre-mining forest.

General characteristics of the Darling Range

Physiography

The jarrah forest extensively occupies the western region of the Darling Range (Figure 1). The Darling Range itself was formed from a marginal upwarping of the Yilgarn Block, a relatively stable shield area which forms a major part of the Great Plateau of Western Australia. The Darling Range is bounded on the west by the Darling Scarp at an elevation of 250 m and rises to 400 m on its highest plateau remnants, these altitudes only being surpassed by isolated monadnocks. Its eastern boundary is delineated by a belt of lower country, separating it from the gradually rising plateau of the interior.

The Darling Range is not only an area of greater elevation but also of greater relief than the land immediately to the east. It is generally characterized by sharply incised drainage lines forming dense drainage networks which are functional in normal winters. The depth of incision is greatest at the Darling Scarp and decreases progressively from V-shaped to flat-floored valleys in going eastwards. Towards the Meckering Line (Figure 1) many of the more extensive divides are upland areas of low relief with such features as lakes and swamps. East of the Meckering Line the drainage is sparse, open and sluggish, with chains of salt lakes in the main trunk valleys. Only in exceptionally wet years do these flow into the drainage downstream of the Meckering Line.

The bedrock geology of the Darling Range is principally granite with minor belts of metamorphosed sedimentary and volcanic rocks. The granite is frequently intruded by thin sheet-like dolerite dykes, particularly adjacent to the Darling Scarp. The presence of the dolerite dykes is a factor in controlling soil type and geomorphology.

Figure 1. Physiography of South-Western Australia (adapted from Mulcahy, 1973)

Soils

The soils of the jarrah forest are dominated by upland laterites which typically consist of ironstone gravels in a sandy matrix overlying concreted or unconsolidated laterite of 2-10 metres thickness.

This in turn is underlain by a deep pallid clay horizon which is succeeded by weathered parent material above the bedrock. In general, the gravels tend to become finer downslope, sometimes grading into sandy yellow earths in the lowest positions. In the more incised valleys, erosion has led to the exposure of various weathered and unweathered materials, movement and sorting of detritus, and cementation. As a result, the interfluves are extensively occupied by the laterite mantle and the valleys show morphology and soils dependent on the amount of local relief, the colluvium on slopes, the degree of stripping of the weathered mantle and the geological nature of the substrate. The range of soils occurring here include red and yellow podsolics and red and yellow earths.

Climate

The climate of the jarrah forest is typically Mediterranean with mild, wet winters and hot, dry summers. The mean annual rainfall decreases from west to east. On the basis of this trend, the region has been divided into high rainfall (above 1100 mm), intermediate rainfall (900-1100 mm) and low rainfall (700-900 mm) zones (Figure 2). About 80% of the annual rainfall occurs in the six months from May to October. On the other hand, 80% of pan evaporation (which is an approximate measure of potential evaporation) occurs in the six months from November to April. Average monthly rainfall only exceeds average monthly pan evaporation for 5 months of the year in the high rainfall zone and for 4 months of the year in the low rainfall zone.

Forest hydrology

Forest hydrology refers specifically to the complex water cycle within the forest. Although there have been many world-wide studies of forested catchments, the jarrah forest presents a unique environment. To evaluate the effects of major land use changes in the forest, such as bauxite mining and rehabilitation, it is necessary to gain a clear understanding of the hydrology of the undisturbed forest.

The hydrological cycle of the jarrah forest is illustrated in Figure 3. Precipitation (which is almost entirely rainfall) may take one of several paths. Some rainfall is intercepted by the vegetation canopy where it is either held and subsequently evaporated or drips from the canopy as throughfall. Some rainfall is intercepted by the stem and branches and is either absorbed by the bark or runs down the trunk as stemflow. The remaining incident rainfall falls between canopies directly to the ground surface. In heavier storms most of the rainfall finds its way either directly or indirectly to the soil surface where it either infiltrates or runs off. Infiltrating rainfall becomes part of the soil water. Soil water is either stored in the unsaturated zone, absorbed by roots and transpired, evaporated at the soil surface or it recharges a saturated zone. Our current understanding of these processes is described in the following.

Rainfall and evapotranspiration

Rainfall characteristics

In addition to mean annual rainfall, which varies from about 1300 mm to 700 mm across a west-east transect of the forest (Figure 2), the variation in annual rainfall is important. For example, at Bannister (in the low rainfall zone) 341 mm was recorded in 1969 and 1157 mm in 1917, whereas at Jarrahdale (in the high rainfall zone) 723 mm was recorded in 1914 and 2169 mm in 1917. In such exceptional years, or more importantly in a succession of drier-than-average or wetter-than-average years, the forest system is likely to exhibit its extremes of behaviour.

Interception

Renewed interest is being focused on interception as a mechanism of water loss, since intercepted water evaporates several times faster than transpired water in the same conditions. Greenwood (pers. comm) has recently obtained a preliminary measurement of interception loss from jarrah clumps left after clearing at North Bannister. His measurements show a mean winter interception loss (June to August) of 28% of rainfall. This loss is higher than the values cited by Feller (1981) for eucalypt stands in the eastern states of Australia, which ranged from 10% to 25% of annual rainfall.

Transpiration

Transpiration of water is the major loss component in the hydrologic cycle of the jarrah forest. Early work showed that the major overstorey species, jarrah (*E. marginata*), maintains a substantial rate of transpiration throughout the arid summer in spite of considerable soil water deficit in the upper profile (Grieve, 1956; Doley, 1967). It does this by extracting soil water

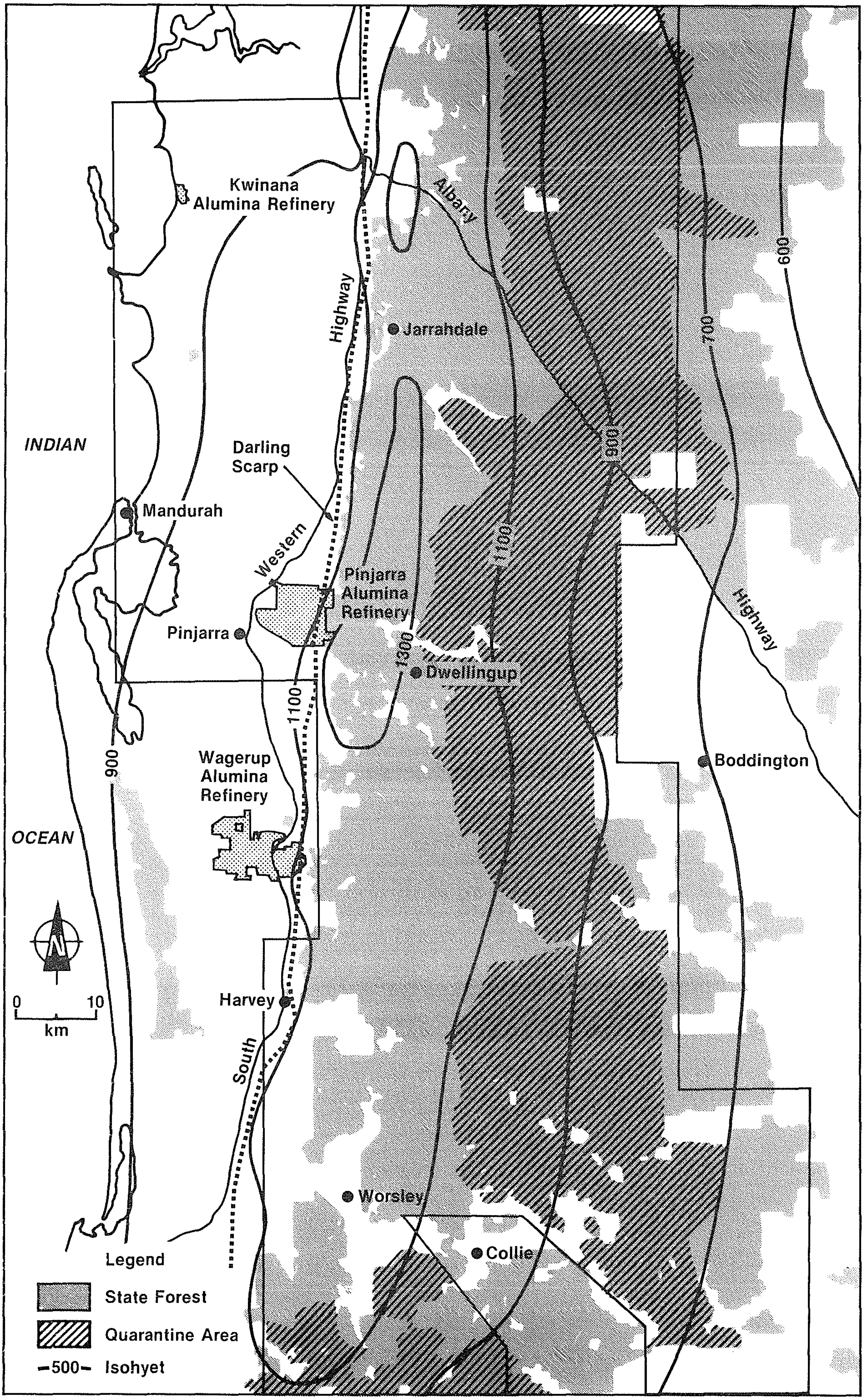

Figure 2. Average annual rainfall isohyets across the northern jarrah forest

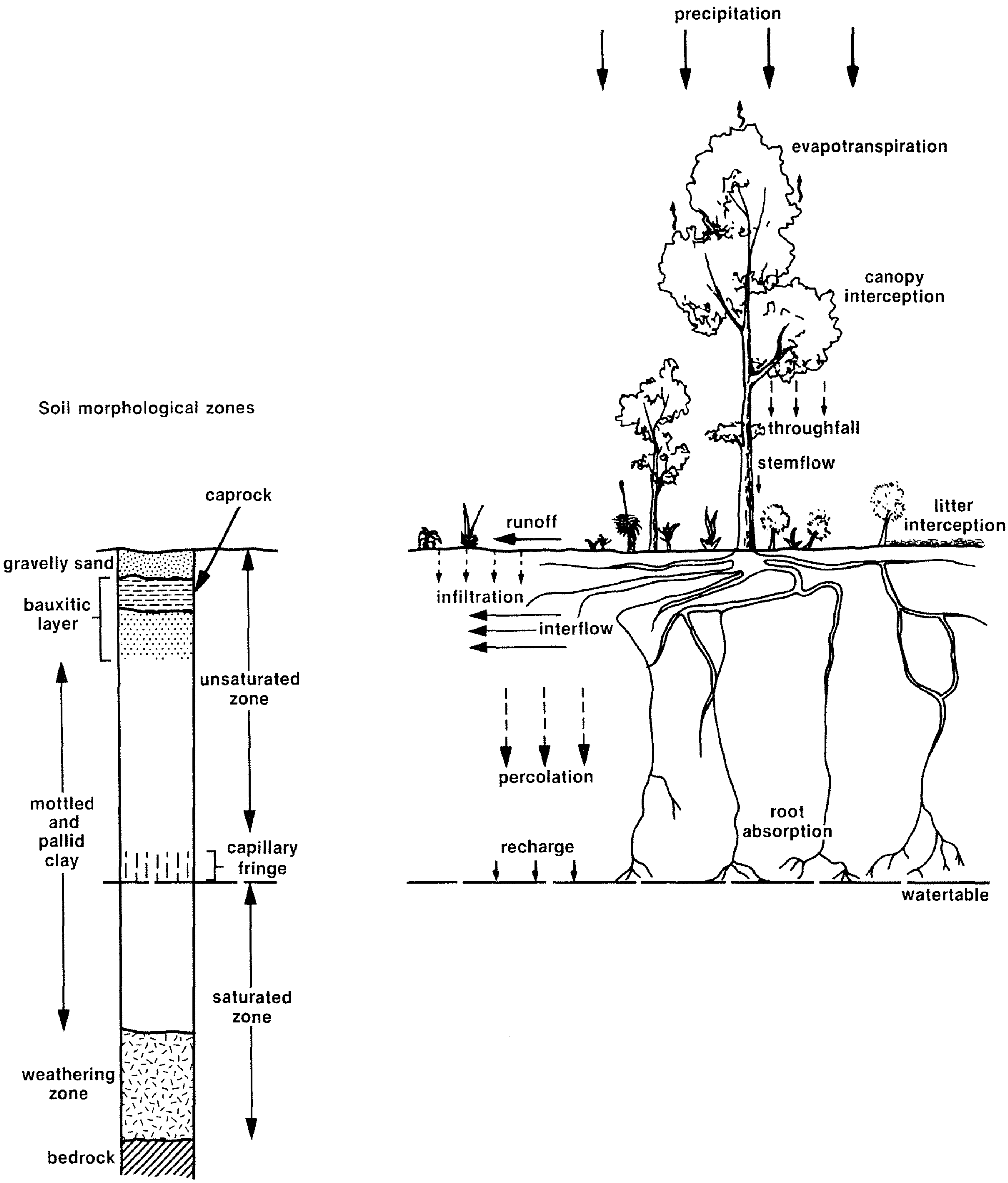

Figure 3. The jarrah forest hydrological cycle and soil morphological zones (not to scale)

from the deep pallid zone clay. Dell *et al.* (1983) have described vertical channels in the profile which facilitate deep root penetration. At one site in the high rainfall zone they observed fine root occupation over the full 40 metre depth of the profile.

Recent work has focused on the processes regulating transpiration. Jarrah has distinctive seasonal and diurnal patterns of stomatal control over transpiration. Using porometers, Ridge (1980) and Colquhoun *et al.* (1984) have demonstrated that jarrah is able to sustain higher levels of leaf conductance (mainly determined by the degree of stomatal opening) than other jarrah forest tree species. In comparison to *E. calophylla* (marri) this is only apparent on the hottest summer days, whereas *E. wandoo* exhibits partial stomatal closure and hence lower conductances throughout the summer. One of the major regulating processes involved in these patterns is the responsiveness of conductance (i.e. the stomata) to the evaporative potential of the atmosphere. Jarrah is relatively insensitive to evaporative potential. This relationship, and others regulating transpiration, are now being quantified using the ventilated chamber technique.

Greenwood (pers. comm.) has recently used the ventilated chamber technique to measure evapotranspiration from the understorey and ground layer at a one hectare site on the Del Park research catchment. The understorey tree *Banksia grandis* evaporated 16%, and the ground layer (groundflora, litter and soil) 37% of annual rainfall respectively, to give a combined evapotranspiration of 51% of rainfall.

Working on the small forested Salmon catchment (Figure 4) near Collie, Sharma (1983) estimated evapotranspiration from the difference between rainfall and the summation of streamflow, soil water change and groundwater change. Actual evapotranspiration during winter (2.9 mm/day) was greater than during summer (2.2 mm/day), despite the higher summer evaporative potential. Sharma postulates that this is due to high interception losses in winter.

Stemflow

Although stemflow is not regarded as a major hydrologic component in the jarrah forest, it has the important feature of concentrating rainfall to the base of the trunk which leads to preferential infiltration. No measurements of stemflow have yet been recorded in the jarrah forest.

Groundwater recharge

Infiltration

The infiltration capacities of the Darling Range soils are highly variable but are generally of such magnitude that they are rarely exceeded by rainfall intensities. For example, the infiltration capacities in Wights catchment (Figure 4) range from 4 mm/hr to 900 mm/hr with a mean of 140 mm/hr. Thus, in general, rainfall will infiltrate the soil rather than become overland flow.

Soil water storage

Soil water storage is a particularly important hydrologic component with respect to bauxite mining which permanently removes 4-5 metres, and on rare occasions as much as 15 metres, of the soil. In the undisturbed situation, seasonal changes in soil water storage in the permeable surface soils are a major component of the water balance. For example, Sharma (1983) measured an unsaturated soil water storage of about 250-300 mm for Salmon catchment which absorbed and subsequently released to transpiration between 27% and 40% of winter rainfall over the period 1974-78. The major variations in soil water storage occurred in the surficial soil due to the low permeability of the clay subsoil.

The high soil water storage of undisturbed forest areas was also demonstrated by the January 1982 rainfall event, when less than 8 mm of the 190 mm rainfall which fell on Salmon catchment discharged as streamflow.

Preferential flow in root channels

In the jarrah forest, old root channels have the ability to transmit water both vertically and laterally at much faster rates than soil matrix flow. However, the extent of preferential flow remains unquantified.

Johnston *et al.* (1983) undertook an experiment designed to identify the pathways of water movement through a typical high rainfall jarrah forest lateritic profile. At an upland site, some 300 metres from a swampy valley floor, rapid lateral flow was seen to occur in well-defined subsurface 'streams'. Vertical percolation through the subsoil was strongly influenced by the distribution of roots. While most of the root volume was observed in the surface soil, large roots were seen to penetrate vertically into the subsoil and in some cases extended to the watertable. These vertical pathways were only identified in subsoils

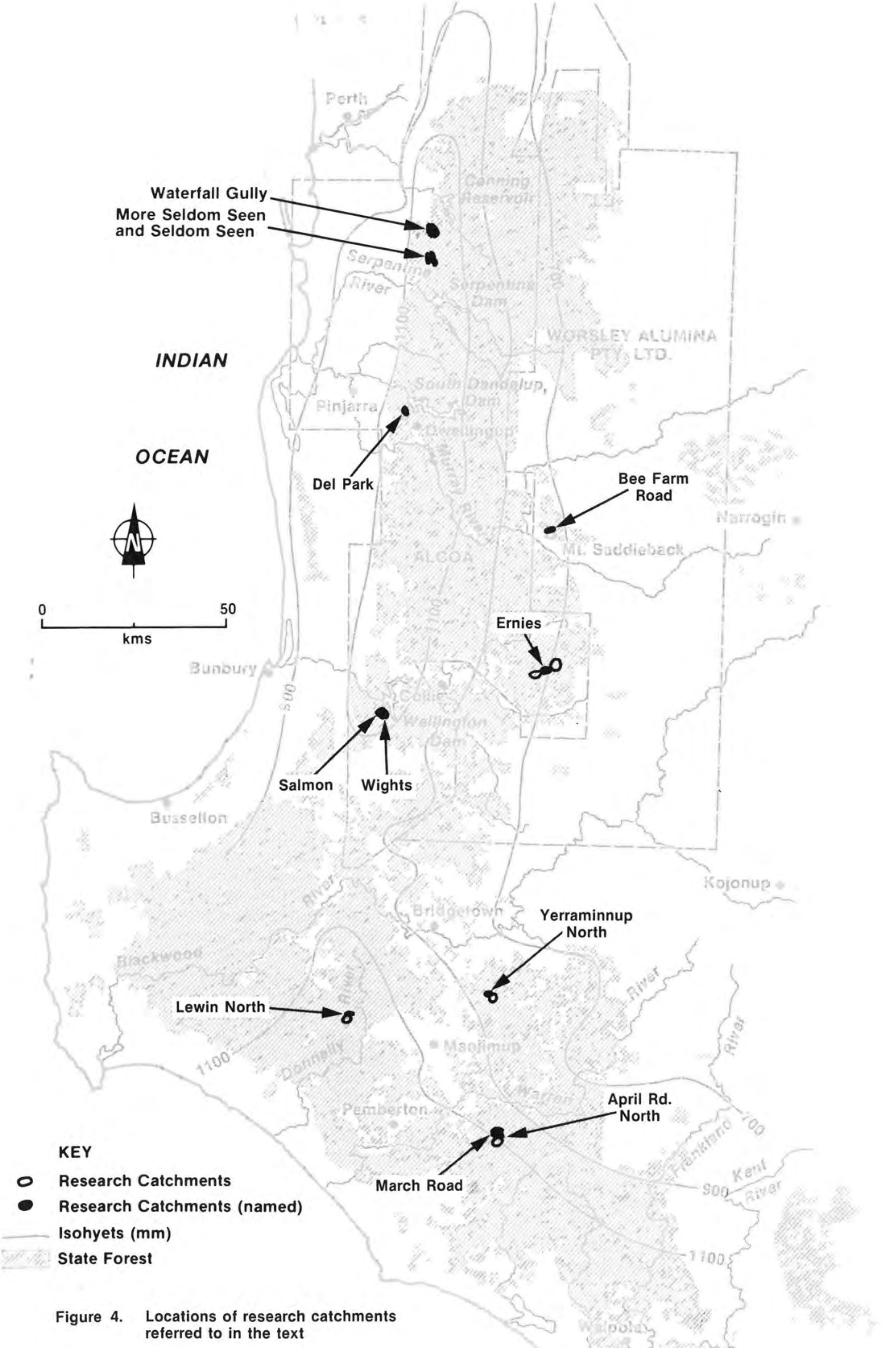

Figure 4. Locations of research catchments referred to in the text

derived from granitic parent material. Observations of tracer penetration indicated that water was passing down the root channels and undergoing sorption into the clay matrix at considerable depths (4-6 metres). In dolerite-derived subsoil, smaller dendritic root systems were found along planar weaknesses but these did not appear to effectively conduct water any distance into the subsoil.

Groundwater recharge

The mechanism of groundwater recharge in the jarrah forest has long been a major concern due to the potential for mobilisation of salts associated with rising groundwater following a land use change. Peck *et al.* (1981), using the assumption that current water and chloride distributions through the landscape are in a steady state, conclude that some water must be 'injected' at depth into the soil matrix to explain the observed distributions. Water movement through the preferred pathways described above provides a mechanism for this and, in addition, explains the often rapid response to rainfall of groundwater systems. A necessary condition for the operation of vertical preferred pathways is the development of a perched aquifer in the upper soil horizon. Such perched aquifers have been observed in the jarrah forest.

The magnitude of groundwater recharge, even in the high rainfall region, is small. For Salmon catchment between 1974-78, only in the wet winter of 1974 was groundwater recharge evident, and then only at 2.5% of winter rainfall. In the following drier years, net extraction of groundwater occurred. At a transect near Dwellingup, groundwater recharge has been estimated to range between 1% of rainfall at upslope locations to 9% for the lower slopes where the groundwater is much closer to the surface (Martin, 1982).

Previous reviews of groundwater monitoring have also indicated an inverse relationship between landscape position and seasonal watertable response. Martin argues that groundwater recharge at sites with deep soil profiles has a higher component of matrix flow relative to preferred pathway flow, in comparison with shallower profiles.

Streamflow generation

Overland flow

Overland flow that is generated when the infiltration rate is exceeded is a major contributor to surface runoff in many parts of the world. However, it is considered to be almost insignificant for jarrah forest soils. The widespread sandy and gravelly surface soils have very high infiltration capacities. Generally only low in the landscape, where finer material has accumulated, do lower infiltration capacities give rise to the possibility of overland flow during high rainfall events.

Near-surface lateral flow

The lateral flow of water through the upper soil horizon is considered to be the major source of streamflow in the jarrah forest. Stokes and Loh (1982) calculated that over 90% of Salmon Brook streamflow originated from lateral shallow subsurface flow.

Lateral flow appears to occur mainly as saturated throughflow (although the unsaturated component has not been measured). This results from a perched aquifer forming in the sandy gravel or loamy surficial soil above a concreted lateritic caprock or a relatively impermeable clay horizon.

Variable source areas

The concept of variable source areas of runoff has been prominent in hydrologic literature for the past decade. It refers to the area of saturation of surface soils which, being impermeable, provides a mechanism for fast overland flow to stream channels. The surface soils become saturated when permanent or perched groundwater intersects the surface and, particularly in respect of the latter, can vary dramatically in areal extent during storms. These saturated areas are particularly effective in producing storm runoff because they usually extend outwards from streamlines in valley bottoms and convergent headwaters.

Stokes and Loh (1982) showed that only about 6% of Salmon catchment (Figure 4) became saturated during the winter of 1981 and overland flow only comprised 2% of the annual streamflow. On this basis the variable source area mechanism does not seem to be highly significant with respect to streamflow volumes in the jarrah forest. However, instantaneous flood peaks were clearly dominated by the intensity of short-term rainfall falling on this small saturated source area of the catchment.

Groundwater flow

Groundwater monitoring has always been a major part of hydrologic research in the Darling Range as groundwater discharge is the major source of salt in streamflow. From this monitoring, a general picture of groundwater occurrence and behaviour has been assembled for the region.

In the high rainfall zone, extensive permanent groundwater systems are normally found in the freshly weathered parent material above bedrock and in the lower section of the pallid clay horizon. Figure 5 shows a typical groundwater system (Wights catchment when forested) which extends over about 90% of the catchment area. Hydrographs of individual bores usually respond to seasonal winter rainfall, peaking in October-November and reaching a minimum in May-June.

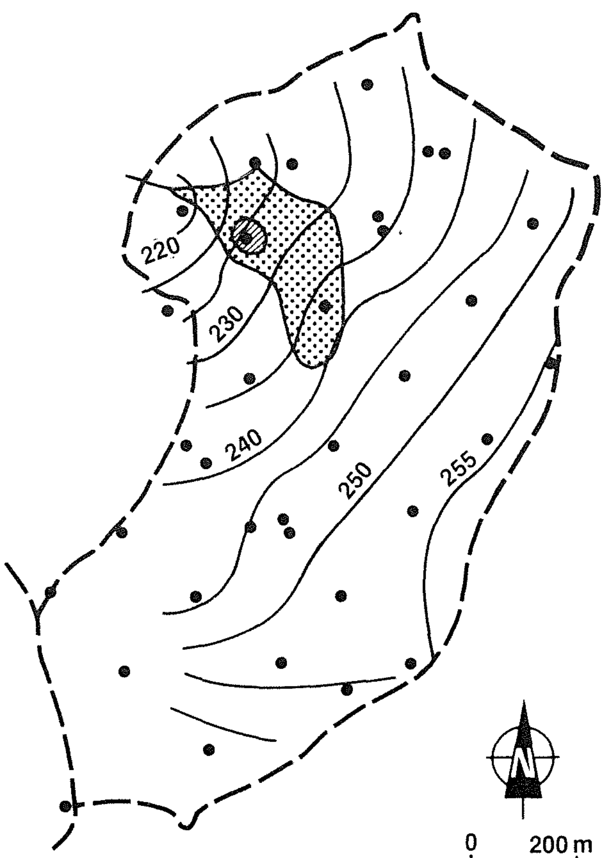

Figure 5. Groundwater elevations on Wights catchment before clearing (after Sharma *et al.*, 1982)

Large variations in the seasonal response of bore levels occur both spatially and between years (Sharma *et al.*, 1982). Low in the landscape, bedrock frequently outcrops and soils are often shallow (Bettenay *et al.*, 1980). This characteristic forces groundwater to discharge at the surface within first or second order stream basins. Streamflows are rarely perennial, even in the high rainfall zone. Evapotranspiration by vegetation flanking the streamlines is usually larger than groundwater discharge. However, where local geological characteristics such as dolerite dykes occur, groundwaters may converge to prolong stream baseflows through the summer.

In the low rainfall zone essentially the same processes transmit water through the landscape, but significant differences in available water, recharge, evaporative demand and bedrock geometries affect the occurrence and behaviour of groundwater. Deep drilling indicates that groundwater rarely covers more than 50% of the catchment and, where present, occurs in bedrock depressions and near the catchment outlet (Stokes, 1983; CSIRO unpublished data). The groundwater does not normally discharge to streams and in fact often lies 15 metres or more below the stream invert at the catchment outlet. The absence of groundwater discharge results in streams ceasing to flow at least six weeks prior to similar streams in the high rainfall zone.

The intermediate rainfall zone represents a variable transition zone between the high and low rainfall regions. Depending on local topography, hydrogeology and rainfall, groundwaters may or may not discharge to streams.

Salt storage

The amount of salt (mainly NaCl) stored in the soil profile generally increases in moving east from the Darling Scarp (Figure 6). The origin of this salt is mostly through rainfall deposition and dry fallout (Hingston and Gailitis, 1977). The concentration of salt in rainfall decreases with increasing distance from the coast.

A strong correlation between annual rainfall and salt storage has been demonstrated by Stokes *et al.* (1980) (Figure 7). The soil solute concentration, defined as the total quantity of solute in the soil divided by the total quantity of soil water, is seen to increase dramatically below 900 mm annual rainfall.

Predictions of salt storage from climatic and terrain characteristics have been undertaken for the principal bauxite region, extending from Armadale to Harvey and east to Boddington, by Alcoa. A non-linear regression using the single parameter 'direct distance from the Darling Scarp' accounted for 88% of the salt storage variations in this region (Slessar *et al.*, 1983).

Johnston (1981) analysed the salt content of 61 soil profiles in the bauxite mining lease area. In the cores from higher rainfall areas there is a clear progression from low salinity, monotonically increasing profiles in the upper landscape to bulge profiles and greater salinities in the lower landscape (monotonic and bulge profiles are shown in Figure 6). This appears to reflect the groundwater recharge-discharge cycle in the high rainfall zone. In the lower rainfall zones the progression is not so obvious. Here, high salinity bulge profiles not only occur in the valley floors but also high in the landscape. Within the soil profile the pallid clay zone has the greatest salinity and the duricrust the least.

The mechanism of salt accumulation in

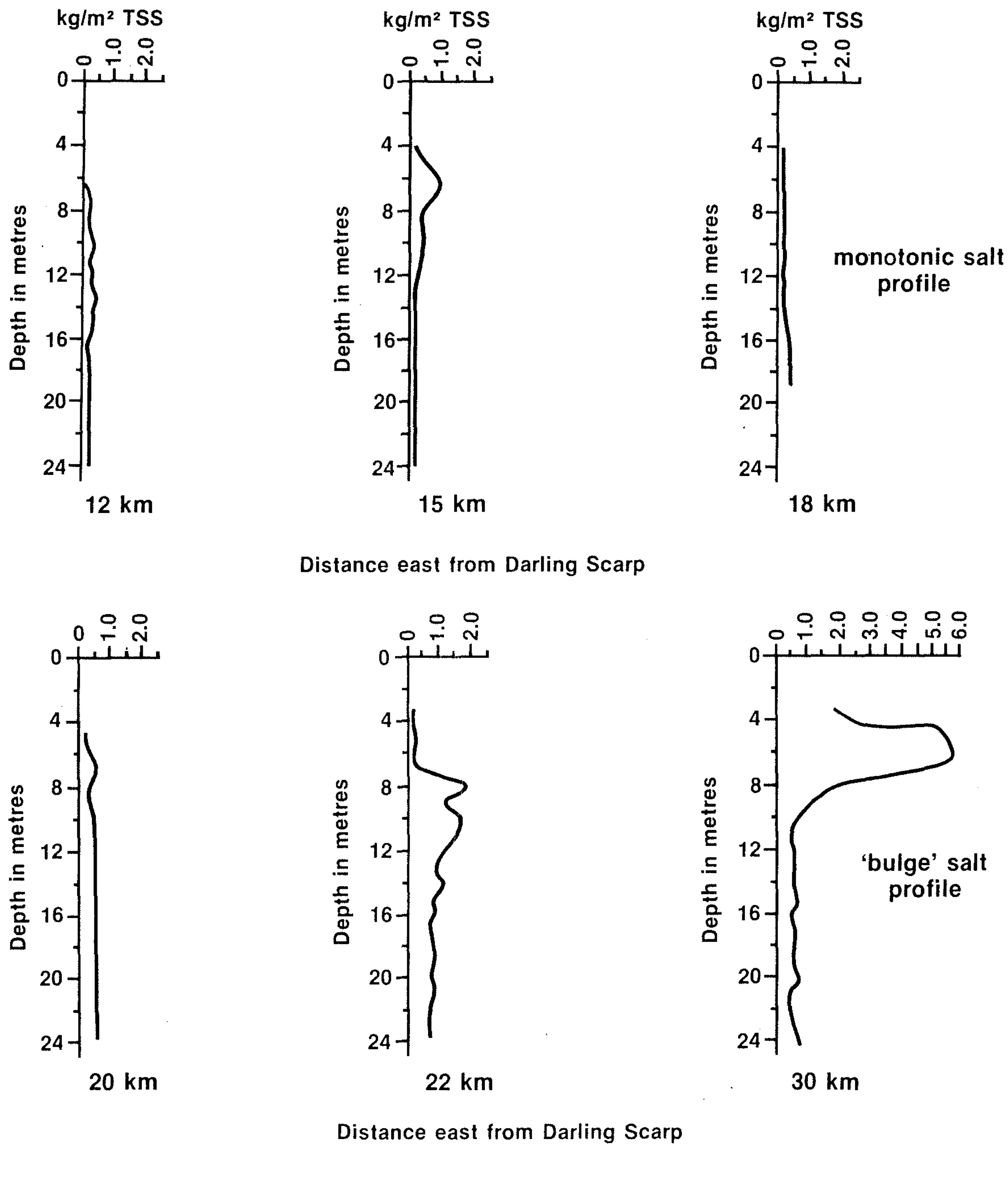

Figure 6. Variation in total salt storage along a west-east transect of the jarrah forest (adapted from Shea & Herbert, 1977)

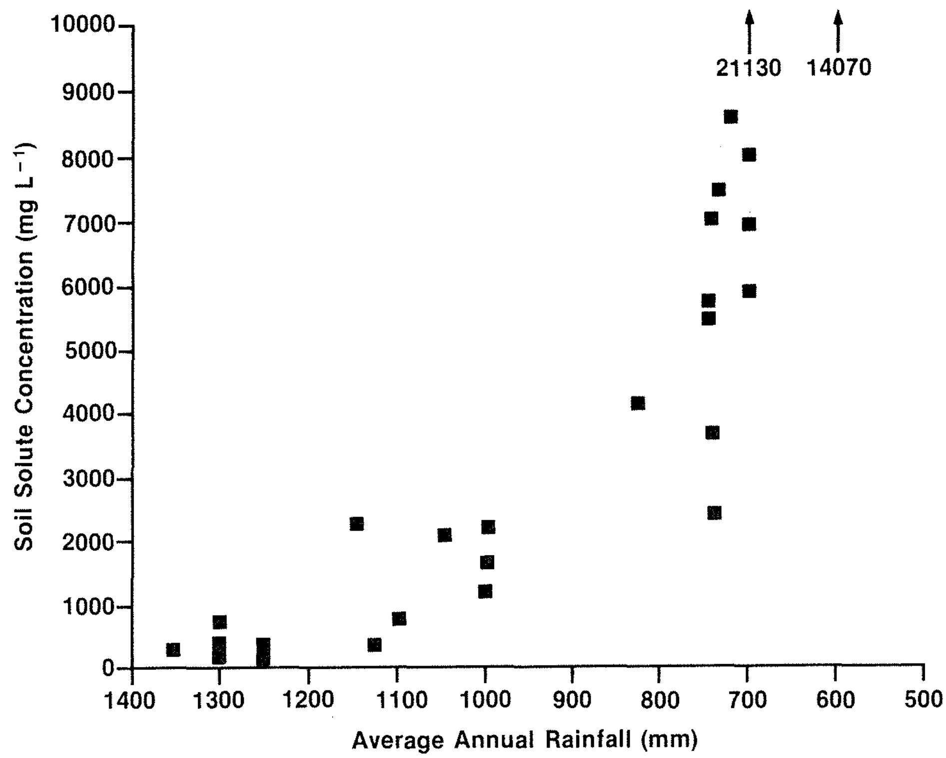

Figure 7. Variation in solute concentration with mean annual rainfall (after Stokes *et al.*, 1980)

the soil profile remains uncertain although it is generally considered to be due to inadequate leaching of the soil matrix. In the bulge profile the salt maximum may be a consequence of water extraction by tree roots causing little or no convective water movement in the bulge section of the profile. This contention is supported by the theoretical analyses of Peck *et al.* (1981) who also point out that water may by-pass the bulge horizon via root channels.

Catchment water and salt balances

Despite the complexity of the hydrology of the jarrah forest in terms of the multitude of processes and the variability of individual properties, the effects of land use changes at the 'macroscopic scale' can be effectively measured by catchment responses.

Seven forested catchments which are distributed across the three rainfall zones, and for which streamflow and stream salinity have been recorded, are listed in Table 1.

Table 1. Annual mean surface water and chloride balances of selected forested catchments (adapted from Loh *et al.*, 1984)

Catchment	Period of record	Long-term mean rainfall (mm)	Annual means for period of record: Rainfall (mm)	Streamflow (mm)	Streamflow/Rainfall (%)	Chloride Input (tonne/km^2)	Chloride Output (tonne/km^2)	Chloride Output/Chloride Input (%)
Waterfall Gully	1966-81	1300	1048	297	28.3	8.91	18.5	208
Salmon	1974-81	1190	1064	111	10.4	6.56	10.3	158
March Rd	1976-81	1050	979	84.9	8.7	6.86	5.7	82
April Rd North	1976-81	1060	1012	73.8	7.3	6.92	3.1	45
Yerraminnup North	1975-81	840	757	17.3	2.3	4.54	0.88	19
Ernies	1974-81	725	685	11.4	1.7	2.73	0.75	28
Bee Farm Rd	1975-81	740	666	1.4	0.2	3.33	0.56	17

It is apparent that catchment yield decreases rapidly in moving eastwards to lower rainfall zones. Also, it is evident that chloride output exceeds chloride input for the high rainfall zone but is less than chloride input for the intermediate and low rainfall zones.

The mean surface water salinities of thirty forested catchments classified by rainfall zone are shown in Table 2. The highest and most variable naturally occurring salinities are in the intermediate zone. The low rainfall zone exhibits the lowest mean and variance of stream salinity, despite its high soil salt storage.

The effect of clearing for agricultural development on salinity is shown for the high and low rainfall zones in Table 3. Little change in salinity is evident for the high rainfall zone but dramatic increases in stream salinity occur in the low rainfall zone.

Interpretation of salinity observations

The variation in hydrological properties in moving on a west-east transect across the jarrah forest is illustrated in Figure 8. The salinity observations may be interpreted in the following way.

In the high rainfall zone, soil salt storage is small and groundwater salinity is low. Thus despite the relatively high proportion of groundwater discharge in this zone, streams are fresh. Even in the extreme situation of heavy clearing, stream salinity does not increase significantly. The fact that chloride output exceeds chloride input probably indicates relatively recent disturbances to the chloride balance by logging and dieback disease. As regards the mechanisms of solute transport in the high rainfall zone, it is clear that soil water can move through the soil profile via preferred pathways and matrix flow to leach salts to the groundwater, which subsequently discharges them to streams. This process keeps this region well leached of salts.

In the low rainfall zone, soil salt storage is very high, groundwater salinity is moderate and stream salinity of forested areas is low. The low stream salinity is due to the fact that groundwater seldom discharges to streams in this zone, and often lies at considerable depth below the stream invert. The groundwater usually resides in the more permeable weathered zone adjacent to the bedrock, where little salt accumulation has occurred. In areas where the forest has been cleared for agriculture, the groundwater and soil solute concentrations are comparable because the groundwater has risen into zones of high soil salinity. The high accumulation of salt in the soil profile of this low rainfall zone is partly due to there being insufficient soil water movement to effectively leach the soil profile.

In the intermediate rainfall zone, the situation lies somewhere between that of the high and low rainfall zones. This zone is

Table 2. Mean and standard deviation of runoff salinities of fully forested catchments by rainfall zones (adapted from Loh *et al.*, 1983)

rainfall zone	mean salinity (mg/L TSS)	standard deviation of salinity (mg/L TSS)	number of catchments
high	129	27	16
intermediate	192	85	8
low	107	22	6

Table 3. The effects of clearing on catchment runoff salinity in high and low rainfall zones (adapted from Loh *et al.*, 1983)

rainfall	level of clearing (%)	mean salinity (mg/L TSS)	standard deviation of salinity (mg/L TSS)	number of catchments
	0	129	27	16
high	<50	160	37	9
	>50	230	85	2
	0	107	22	6
low	<50	1605	585	6
	>50	3231	530	7

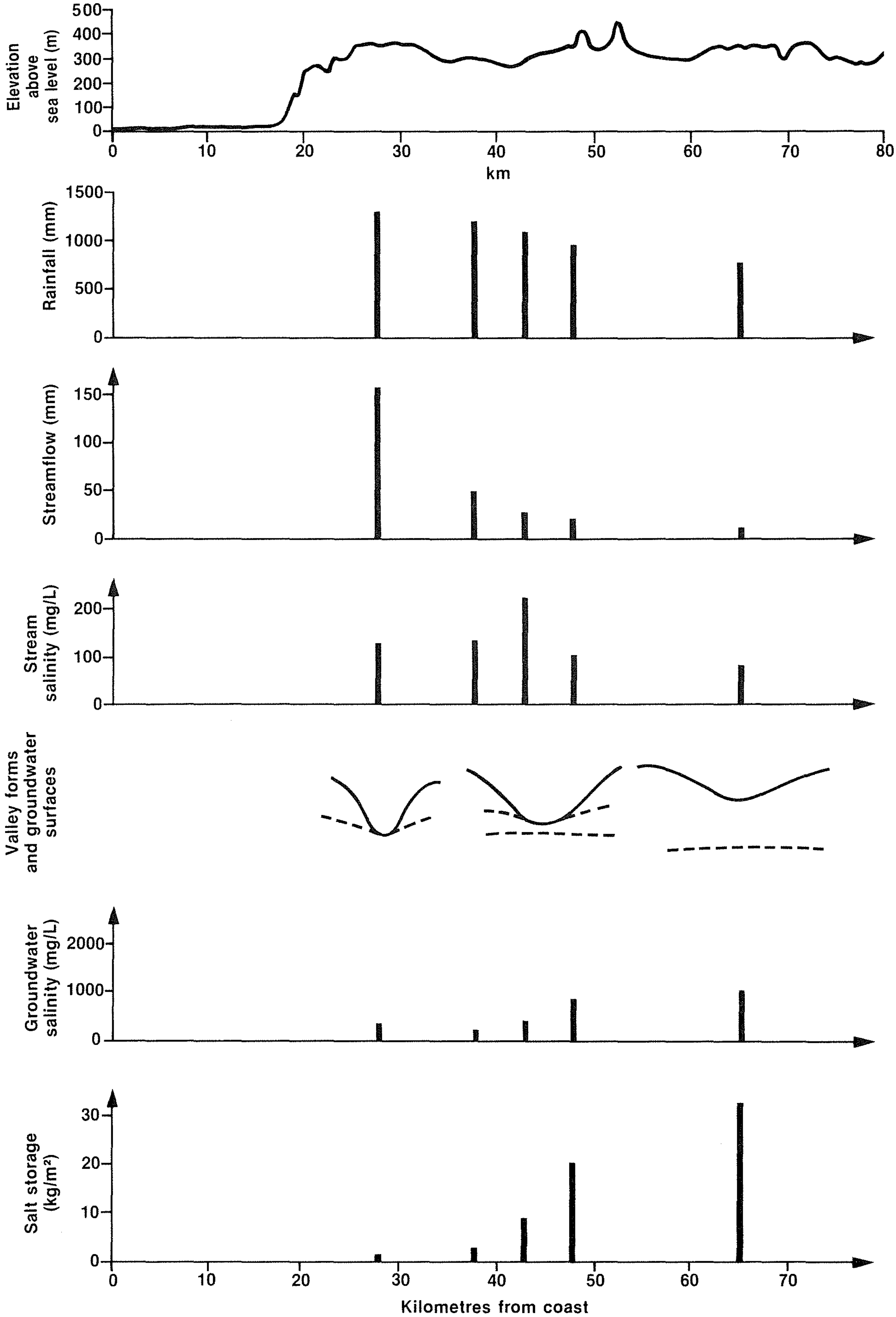

Figure 8. Variation in hydrosalinity parameters on a west-east transect across the northern jarrah forest

characterized by a high variability in soil salt storage, groundwater salinity and stream salinity. This variability is related to local topography and subsurface geology and to the existence or otherwise of groundwater discharging to the stream.

The jarrah forest ecosystem

The jarrah forest has frequently been described as unique and fragile. Botanically the region is quite unusual. Along with the vegetation of adjacent areas, it has evolved in isolation on a stable land surface over a long period of time. According to Barlow (1981), its outstanding features are a high degree of endemism, diversity and scleromorphy. The tree stratum does not display the diminutive scleromorphic stature. Diels (1908) first recognised that, in comparison to other areas of Mediterranean climate, the overstorey (mainly jarrah) is of exceptional height. This enhanced tree growth appears to arise from greater water availability due to an unusual combination of favourable attributes of its environment, i.e. high rainfall, flat topography and a deep water retaining profile. No other Mediterranean area combines all these favourable attributes (Di Castri and Mooney, 1973).

The jarrah forest's reputation for fragility arises from its striking vulnerability to the introduced root-rot fungus *Phytophthora cinnamomi*. This pathogen causes dieback, a disease that can eliminate jarrah and many other species on susceptible sites (Podger, 1972). Another factor contributing to its reputation for fragility is that reduction in forest cover by disease or land clearing can lead to salinisation.

Increasing land use pressures have led to an intensification of jarrah forest research in recent years. One major objective of this research is to minimize the adverse impact of mining and to put rehabilitation onto a sound ecological basis.

Phytogeography

The significance of climate, landform and soils in determining the distribution of plant species and communities in the northern jarrah forest has been recognized by many workers. Havel (1975 a,b) refined the understanding of these relationships by identifying site-vegetation types by principal component analysis. He found that the site factors topography, rainfall, soil fertility and soil texture formed a multi-dimensional continuum along which vegetation continuously varies. This continuum can be broken into segments, each with a characteristic set of indicator species. He specified some twenty site-vegetation types to cover the whole northern jarrah forest.

The major gradients in the environmental continuum are rainfall, which declines steeply from west to east, and soil fertility and texture, which generally improve with dissection of the landscape (which is more advanced in the west). Knowledge of vegetation changes along these gradients is valuable in understanding jarrah forest ecology but is very difficult to present concisely and is too complex as a guide to management. For this reason the northern jarrah forest has been divided into six management categories according to rainfall and geomorphology (Forests Department, 1976). These categories, their physical characteristics and site-vegetation types are as follows:

(i) Dissected river valleys and scarp in the high rainfall zone:
On the scarp and adjacent dissected valleys, jarrah (*Eucalyptus marginata*) is confined to the deeper soils. The major tree species are wandoo (*E. wandoo*), *E. laeliae*, *E. haematoxylon*, *E. lane-poolei* and *Allocasuarina heugeliana*.
In the valleys of major rivers yarri (*E. patens*) and marri (*E. calophylla*) often become dominant over jarrah. *E. rudis* and *Banksia littoralis* var. seminuda become prominent. Tall Bossias and Acacias characterize the understorey.
The site-vegetation types Q, U, C, G and R (Havel, 1975a, b) predominate in these areas.

(ii) Lateritic uplands in the high rainfall zone:
This area consists of tall jarrah with some marri, and a tree understorey of *Banksia grandis*, *Allocasuarina fraserina* and *Persoonia longifolia*. Minor upland valleys, sometimes with sandy surface soils and often perennially wet and giving rise to streams, have a cover of *E. patens* and *E. megacarpa*. Types T, S and P predominate in this area, merging into types D, W and C in shallow valleys.

(iii) Dissected river valleys in the low rainfall zone:
As rainfall decreases, jarrah is gradually replaced by wandoo, and the understorey of tall Bossias and Acacias

gives way to shorter Acacias and Gastrolobiums. Site types M, L and Y displace the western valley types.

(iv) Lateritic uplands in the low rainfall zone:
This area is dominated by jarrah with wandoo becoming important in the more dissected lateritic slopes. The height and density of this forest progressively diminishes as does its content of Banksia, Persoonia and Allocasuarina understorey. *E. drummondii* forms a low open woodland on truncated profiles. Site types P, Z and H become predominant.

(v) Broad valleys and depressions in the low rainfall zone:
Seasonally waterlogged valley floors carry thickets of Melaleuca scrub and scattered *E. rudis* trees. They are flanked by either wandoo woodland on heavier textured soils, or by jarrah on sandier soils. Areas of deep, strongly leached sands carry a low woodland of *Banksia attenuata*, *Banksia menziesii* and *Nuytsia floribunda*. Site types F, J, B, Y and A occur in these areas.

(vi) Monadnocks in the low rainfall zone:
These residual low hills carry vegetation varying from jarrah, marri and *Allocasuarina huegeliana* woodlands, through shrublands to bare basement rock. Site types from adjacent upland forest grade into type G around outcropping rock.

Dieback

Though introduced to the jarrah forest only several decades ago, *Phytophthora cinnamomi* has had such an impact that it is now considered a major factor in jarrah forest ecology and management. *P. cinnamomi* is a soil-borne fungus which thrives in moist conditions and is responsible for the disease called jarrah dieback (Podger, 1972). The fungus requires warm, wet conditions for rapid multiplication and spread (Shea, 1975). Natural spread is by means of motile spores in drainage water. Human activity can greatly assist spread by transport of infected soil such as in nursery stock, logging operations, road making and mining. Elaborate hygiene and quarantine procedures have been developed to minimize these forms of transmission. Human activity can also cause intensification of disease by creation of more favourable site conditions, mainly through disturbance to drainage.

The impact of infection varies markedly with site as follows:

(i) Dissected river valleys: Sites with fertile freely draining loam soils do not suffer disease. Impact in these valleys is therefore restricted to minor occurrences on residual laterite soils.

(ii) Freely draining upland laterites: In the high rainfall zone these sites may be extensively infected but exhibit only moderate disease which removes the highly susceptible *Banksia grandis* understorey but only lightly affects jarrah.

(iii) Upland laterites with impeded drainage: On some laterite soils the shallow (0.5-1.0 m) sheet caprock layer temporarily impedes drainage. Especially after unseasonal summer rain, water perched on this layer can create ideal conditions for fungal activity. Fungal attack is focused on jarrah roots which pass through occasional holes in the caprock. Jarrah is dependent on these roots for summer water. Disease can rapidly destroy these roots resulting in sudden death of jarrah, sometimes extending over many hectares (Shea *et al.*, 1982).

(iv) Upland duplex soils: Perhaps the most extensive high disease impact site is the duplex (gravel over clay) soil profiles which make up the zone transitional from upland laterites to the headwaters of streams in shallow upland valleys. Water seepage from upslope keeps these sites moist well into summer, providing ideal conditions for the fungus. In the high rainfall zone these sites are invariably severely diseased.

Present disease distribution in the forest is markedly biased to the high rainfall zone and to upland valley (type iv, above) sites. Though higher rainfall favours disease, the high rainfall zone has also been exposed to greater potential for disease spread by human activity. It is therefore not clear from present distribution and impact just how vulnerable the low rainfall zone might be. Examples of severe disease of types (iii) and (iv) do exist in the low rainfall zone. The natural occurrence of high impact sites and the spread and intensification of disease due to human activity are crucial issues in the use of this zone.

Fauna

Little comprehensive study of jarrah forest fauna has been undertaken. Species inventory is probably complete for the vertebrates, but far from complete for invertebrates.

Some work has been done to document the impact of fire, particularly controlled burning, on fauna. For example, Schmidt and Mason (1973) found the mammal *Antechinus flavipes* (mardo) to be more common in areas unburned for a long period, reflecting its dietary preference for litter dwelling invertebrates (Majer, 1978). Other work has focused on invertebrates, often considered to be the most sensitive indicators of ecological changes (Springett, 1978; Majer, 1981).

Fauna study in the jarrah forest was expanded following the commitment made by Alcoa and Worsley to do comprehensive fauna surveys prior to mining to provide baseline data against which the impact of mining and rehabilitation could be measured. The Alcoa work has been presented mostly on the basis of comparing rehabilitated pits with adjacent forest (Majer, 1981). This work is discussed in Chapter 5 of this report. Worsley have presented an integrated report of native forest survey results (Worsley, 1981). It includes full discussion of previous work and is of particular value in that it covers the full forest rainfall transect from their refinery in the high rainfall zone to the minesite in the low rainfall zone.

Seed gathering ants are a particular feature of Australian fauna and some plant species, for example the Acacias of the jarrah forest, rely on ants for seed burial and dispersion (Shea *et al.*, 1979). From his extensive study of ants, Majer (1981, 1983) suggests that, due to their prominence, their role in specialized niches and their occupation of higher trophic levels, ants are the most appropriate invertebrate group to act as an index of ecological change.

Dynamic processes

With the exception of the hydrologic cycle, the dynamic processes within the jarrah forest ecosystem are poorly understood. The inputs, storages, fluxes and outputs of energy and nutrients, and the stability and interdependence of these and other processes, have only just begun to be described. Some key subsystems where particular problems occur have been subject to intensive study. Hydrology is one such key area and has been dealt with in the previous section. Another is fire.

Fire is a natural factor in the jarrah forest environment and has important impacts on the energy and nutrient cycles in the ecosystem. All native plants and animals are adapted to, or can readily survive, even quite intense fire. However, European man has greatly altered the natural fire patterns and introduced the risk of loss of life and damage to property. To keep these risks low, forest fuels are regulated by controlled burning. A practice of cool spring or sometimes autumn burns has been developed. These prescribed burns consume fuels when risks are low and operational costs are small (Underwood and Christensen, 1981). After some two decades of this practice, its success in control of wildfire has been well demonstrated but there appears to be some adverse ecological impacts. For example, desirable understorey legumes may be disfavoured, dieback susceptible *Banksia grandis* appears to be favoured and some fauna are disadvantaged (Shea *et al.*, 1979; Shea *et al.*, 1981). Initial research shows that hotter fire may relieve these problems but only at the expense of greater operating costs and some tree damage. Research is continuing.

Ecophysiology

Some aspects of the environment present a greater challenge to plant adaptability than others. Bartle and Shea (1978, 1979) propose that summer drought, physical and chemical conditions of the soil and fire are the key constraints in the jarrah forest environment, and identify the adaptations in jarrah which allow it to dominate the vegetation. In addition, *Phytophthora cinnamomi* is an introduced factor that has now become a major constraint in the environment.

The adaptation of jarrah to these constraints provides some insight into appropriate rehabilitation methods. They are:

(i) Summer drought: The coincidence of extreme summer drought with plentiful but deep and dispersed soil water offers two strategies for plant survival. Some plants exploit the stored water, others rely on adaptations to economize on summer water consumption. Though many jarrah forest species may use elements of both strategies, jarrah relies heavily on the former. Evidence of its exceptional root system and capacity to continue transpiration throughout the summer drought period is reviewed by Dell *et al.* (1983).

The efficiency of the jarrah forest in annually depleting deep soil water opens the potential for growth of tall forest, where otherwise only woodland or heath may survive. It is also a major factor in the process of salt accumulation.

(ii) Soil conditions: The large depth and soil water storage capacity of the jarrah forest profile favours forest growth. However, the attractiveness of this environment is offset by its many adverse physical and chemical characteristics. For example, extensive drilling has revealed that the deep clay subsoil occupied by jarrah roots has a density of 1.6 gm cm^{-3}, a pH of 5.3 $\pm$ 0.5, and salt concentration up to 0.5% by mass. The entire profile including the topsoil is very deficient in plant nutrients. All of these characteristics are generally considered marginal for root growth.

The structure of the profile imposes a constraint on root form. Access for descending roots is restricted to fissures and conduits in the caprock and to channels (1 to 3 per m^2) in the subsoil clay. These channels form zones of high water conductivity which result in deep, variable patterns of recharge (Johnston *et al.*, 1983). They are also the means by which large roots of jarrah gain access to a soil mass whose density otherwise only permits fine root access (Dell *et al.*, 1983).

The full range of adaptations of jarrah which cope with these physical and chemical limitations is not yet clear.

(iii) Fire: Jarrah is remarkably fire resistant. Its thick bark insulates the underlying active tissue from damage during fire. Leaves, twigs and branches may be killed in intense fire but the crown can rapidly regenerate from epicormic buds on undamaged branches and trunk. Jarrah seedlings and saplings may have their above-ground parts destroyed by fire but regenerate readily from a below-ground ligno-tuber.

(iv) *Phytophthora cinnamomi*: Jarrah has no specific resistance to *Phytophthora cinnamomi.* However, where site conditions are not highly favourable for *P. cinnamomi*, jarrah can survive and even remain healthy by use of general disease/injury resistance mechanisms. On some sites management treatments can be carried out to disfavour the fungus and improve the prospect of jarrah survival. For example, reduction in the density of highly susceptible *Banksia grandis* may reduce disease build-up and enable jarrah to survive on sites not highly favourable to disease. On the high impact upland laterite sites with impeded drainage, measures to increase the permeability of the caprock layer are being considered.

Chapter 3
The Potential Disturbance by Bauxite Mining

Location of mining areas

The bauxite mining leases in the south-west of Western Australia are shown in Figure 9. Of the three mining companies holding leases (Pacminex, Worsley, Alcoa) only Alcoa and Worsley are currently mining. Worsley has recently commenced mining bauxite at Mount Saddleback, but their mining programme is not specifically considered in this report.

Alcoa's mineral lease covers 1.2 million hectares of the Darling Range of which 700,000 ha are State Forest. However, over 90% of the estimated bauxite reserves within Alcoa's lease occur in a 400,000 ha area stretching from the Brookton Highway south to the Stirling Dam. Their current mining operations are at Jarrahdale, Huntly, Del Park and Willowdale (Figure 9), which all lie within the high rainfall zone. This zone contains the highest concentration of bauxite ore in Alcoa's lease and has the advantage of proximity to the alumina refinery sites at Kwinana, Pinjarra and Wagerup.

Since bauxite mining began, Alcoa has cleared 3382 ha for mining. Ore bodies tend to be about 10-25 ha in extent and occur as isolated pockets on the flanks of ridges. For this reason only a portion (20-30%) of the forest is actually cleared. In 1982 the rate of clearing was about 300 ha per year. This rate is expected to double by the end of the century.

The mining sequence and soil disturbance

The first step in the mining process is the logging of commercial timber from the proposed mining area. Remaining forest is then bulldozed, stacked and burnt. The topsoil overlying the caprock is removed wherever possible in two stages: the first 5 cm is stripped and transferred directly to a mined area undergoing rehabilitation; the remaining topsoil (typically about 35 cm) is then removed and stockpiled adjacent to the pit being mined. Removal of the topsoil leaves the caprock exposed, which is drilled and blasted. The blasted caprock and the underlying 'friable bauxite horizon' is excavated down to the depth where the reactive silica levels become too high or the alumina grade becomes too low for economic refining of the ore. This can occur at or somewhat above the pallid clay layer depending on local variations in geology. Nevertheless the mining usually involves the removal of 4 or 5 metres of the soil profile, although a depth of 15 metres was reported at one site. Following rehabilitation, the soil profile comprises 30-40 cm of replaced topsoil which grades into a relatively impermeable clay horizon, either abruptly at pit floor level or more gradually through a zone of friable low grade bauxite (Figure 10).

Potential hydrological disturbances

The mining operation strongly disturbs the hydrological cycle of the jarrah forest both within the mined area itself and in adjacent unmined forest. The effects of this disturbance, however, are minimised by rehabilitation, as described in detail in ensuing chapters. In this section some of the potential changes to the hydrological regime and their related hazards are outlined.

- The clearing of native vegetation eliminates interception and transpiration entirely until revegetation is commenced. Even then it will be some time before transpiration of regenerated forest approaches that of the native forest. Moreover, the evapotranspiration from mature regenerated stands may differ significantly from the pre-mined forest.
- Since jarrah is a very deep-rooted species capable of sinking taproots several tens of metres into the clay horizon, its removal will reduce the consumption of soil water deep in the soil profile. A long period may be necessary for alternative species to develop deep roots and they may have quite different patterns of water extraction.
- The removal of the bauxitic laterite profile down toward the clay horizon may have a substantial effect on soil water storage and availability. In the undisturbed situation most of the soil water storage and release occurs in the upper permeable soils. The soil water dynamics within the post-mining soil profile is a topic of future research.

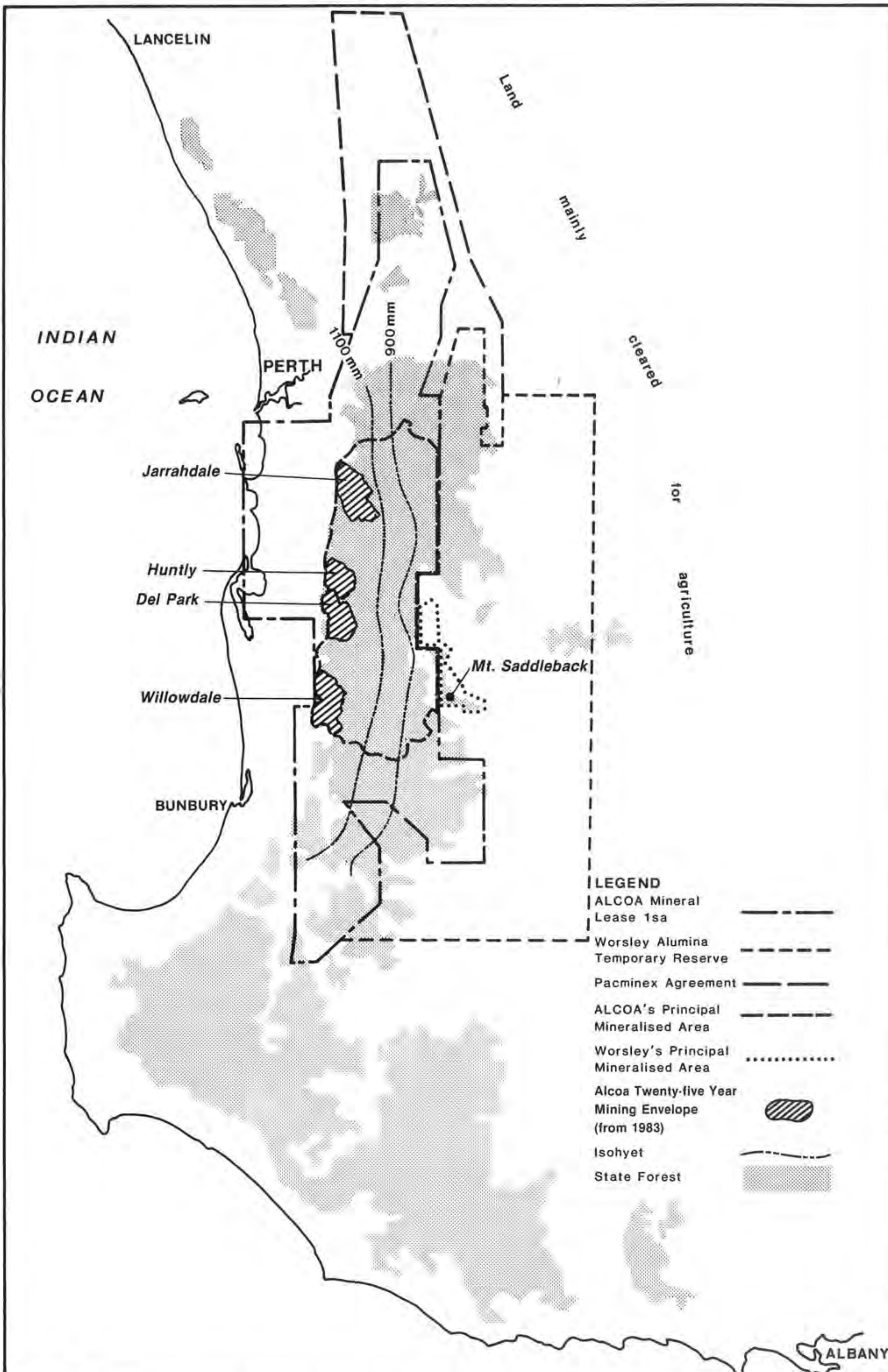

Figure 9. Mineral leases and minesites in south-west Western Australia

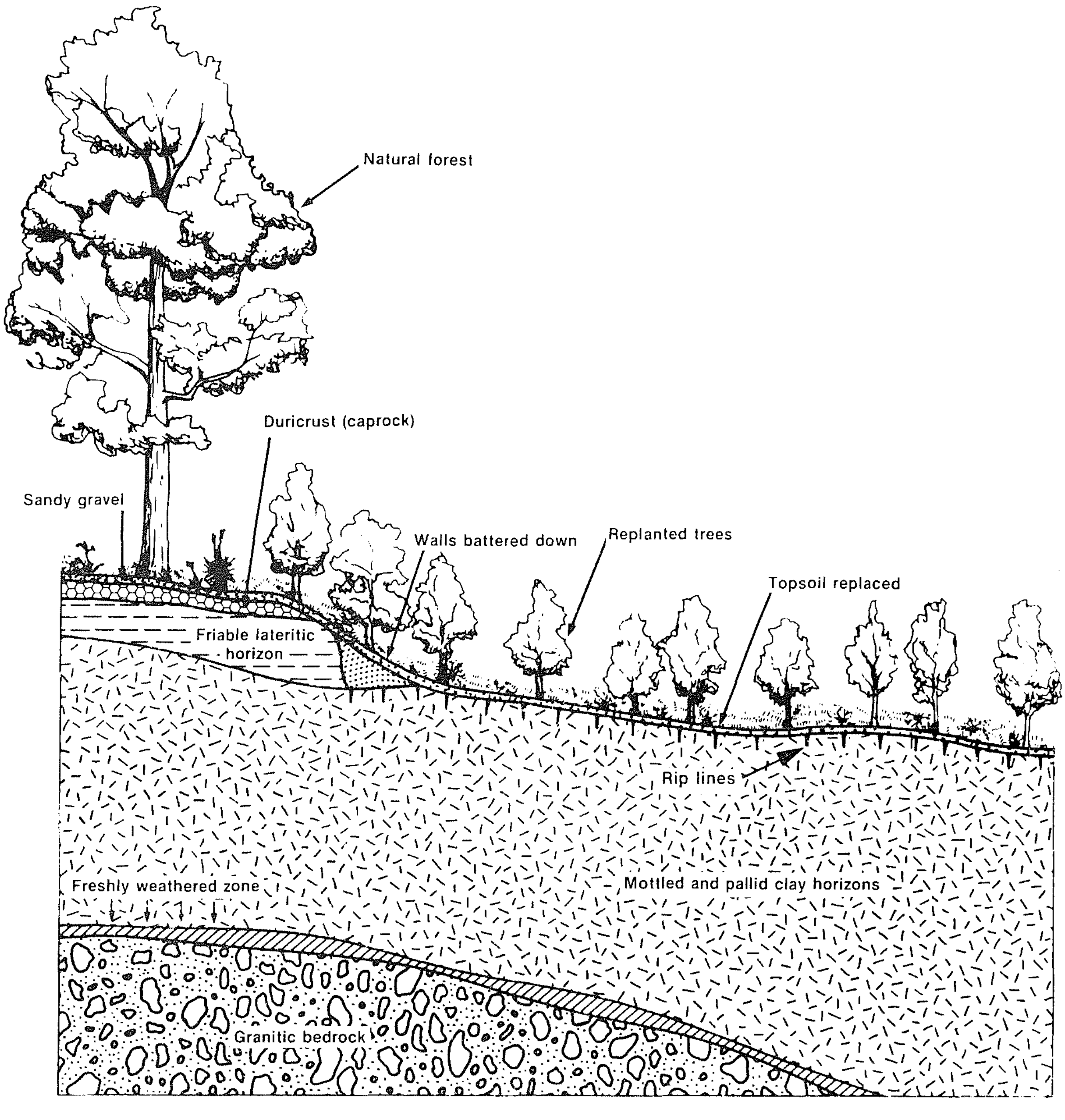

Figure 10. Rehabilitated minepit showing the soil profile before and after mining

- The presence of a relatively impermeable clay horizon near the soil surface generates increased surface runoff and interflow. Associated with this are several possible short-term deleterious effects including soil erosion and turbidity. Increased susceptibility of downslope areas to dieback may also occur.
- The procedure of ripping the pit floors subsequent to mining is currently practised to aid root penetration by seedlings. Ripping the clay horizon also appears to re-open root channels which become sealed during the bauxite excavation phase. Although beneficial to root growth, this procedure aids deep percolation through the soil profile and thus may increase deep groundwater recharge and the potential for salt mobilisation in salt-prone eastern areas.
- Water yield will in most situations increase due to both decreased evapotranspiration and increased surface runoff from minepits. If minepit surface runoff is allowed to discharge through the adjacent hillslopes, this would result in larger saturated source areas which in turn would produce increased peak flows

and a greater potential for flooding. If minepit runoff is discharged directly to streams, unacceptable levels of turbidity may arise until the minepit floors are stabilised by revegetation.

- In salt-prone areas well east of the current mining operation, the salinity of streamflow may increase in response to mining due to rising groundwater leaching salts from the soil. Significant increases in stream salt concentration have not been observed in the high rainfall zone because groundwater and soil salinities are very low.

Forest disturbance

Forest disturbance due to mining ranges from the direct impact in minepits to indirect impacts over the wider landscape in which mining is conducted. The major effects are:

- On the minepits the native forest ecosystem is destroyed and the soil environment profoundly altered. The minepits form upland, clay-floored depressions in what was freely draining, convex topography. The pit floor is heavily compacted and the natural infiltration pattern via vertical channels is disturbed. The pits constitute a completely new site type in the forest and require intensive rehabilitation treatment to control erosion and bring their appearance and productivity up to acceptable standards.

- In spite of the substantial proportion of the landscape in the high rainfall zone which is affected by dieback, there is often relatively little overlap of bauxite with areas of high disease impact. This is because the distribution of high impact sites is biased to lower landscape positions and bauxite to upper landscape positions. For example, Bartle (1976) showed that though some 28% of the Seldom Seen catchment (near Jarrahdale) was in the high impact 'graveyard' category prior to mining, pits were nearly totally confined to low impact or uninfected forest upslope. Thus the direct loss of substantially intact forest is larger than might be otherwise supposed.

- The distribution of bauxite, its contrast with disease distribution (particularly in less extensively infected areas), and the nature of the mining operation all contribute indirectly to degrading the forest by disease spread. The nature and scale of mining, with its massive earth movement, numerous machines and vehicles, and wide dispersal of activities over area and season, provide considerable potential for disease spread. Against this background even the most conscientious application of hygiene may not fully eliminate spread. New infections established in or around pits and access roads generally have scope for natural downslope spread. In addition, the generation of extra surface and subsurface runoff, and the disturbance to drainage and ponding of water in and around minepits and roads, can create localized areas highly favourable to disease.

- Bauxite is widely dispersed across upper landscape positions. Ore is transported along a haul road network, delivered to a central crusher and then carried out of the forest via conveyor or rail. The life of an individual pit is 1-3 years but the duration of major infrastructure may be 10-12 years in any one forest block (25-50 km^2). The intensity of this activity has a major temporary impact upon all land use and management practices. The fragmentation of the previously fairly uniform forest into a patchwork of rehabilitated pits and unmined forest will complicate ongoing management.

Chapter 4
Rehabilitation

Rehabilitation objectives

The Agreement Acts governing Alcoa's first two mining/refining operations (Alumina Refinery Agreement, 1961; Alumina Refinery (Pinjarra) Agreement, 1965) at Jarrahdale and Pinjarra did not have detailed provisions for rehabilitation. Subsequent Acts (Alumina Refinery (Worsley) Agreement, 1973-78; Alumina Refinery (Wagerup) Agreement, 1978) required the companies (Worsley Alumina and Alcoa respectively) to submit Environmental Review and Management Programmes (ERMPs) which, after approval by the State, are legally binding. In both cases the programmes which were approved commit the companies to comprehensive rehabilitation, environmental monitoring and research (Alcoa 1978(b), Worsley 1979). The rehabilitation objective embodied in each programme is to regenerate land that is able to meet the land use requirements of the State. The commitments to rehabilitation embodied in the Wagerup ERMP have also been adopted by Alcoa for the mining operations at Dwellingup and Jarrahdale.

Planning of land use requirements by the State was upgraded in the early 1970s in anticipation of conflict between rapidly expanding, competing uses. A series of public documents was produced, incorporating input from all forest users and presenting a comprehensive but flexible land use plan for the whole forest (Forests Department, 1976, 1977, 1978, 1982).

A system of multiple use was adopted to cater for the maximum range of uses at any location. With this system the problem of compatibility between uses is overcome by assigning priorities to each possible use. Each appropriate land area is allocated a primary or priority use with a range of secondary, largely compatible, uses and tertiary uses which may be permitted if they can be arranged so that they do not compromise the primary use. Incompatible uses are also identified. Each area is known as a Management Priority Area (MPA) and designated by its primary use, e.g. water production MPA.

The system is flexible over time. A tertiary use may be compatible at some times of the year or at some time in the future. The priority ranking is reviewed from time to time.

Current land use allocations for areas in the bauxite mining leases are shown in Figure 11. Mining is designated a secondary use in water production MPAs and a tertiary use in recreation and catchment protection MPAs. Mining is regarded as incompatible with conservation MPAs. Mining will be confined mainly to water production and recreation MPAs for at least three decades. In each case the objective of rehabilitation after mining is to regenerate stable ecosystems and integrated landscapes designed to restore or enhance land use values in accordance with their priority rating. The specific objective for each of the potential uses is as follows:

- *Water values*: To ensure that mined areas provide acceptable water quality and quantity.
- *Timber*: To grow a forest which has the potential for eventual sawlog production.
- *Recreation*: To maintain existing recreational values where possible and to provide increased opportunities for forest-based recreational activities.
- *Protection*: To conserve the residual soils, to control dieback spread, and to ensure that unacceptable fire hazards do not accumulate.
- *Landscape*: To create a rehabilitated landscape visually compatible with the adjoining remnants of indigenous forest.
- *Conservation*: To re-create, in the long term, floral, faunal and soil characteristics compatible with the remnant indigenous forest.

Management of rehabilitation operations

During 1980 the Forests Department coördinated the preparation of the first comprehensive statement of objectives, techniques and 'success' criteria for rehabilitation operations. This prescription became known as 'Rehab. 80' (Underwood, 1980). Annual reviews are carried out to incorporate new information. The current prescription, Rehab. 84, is presented in Ap-

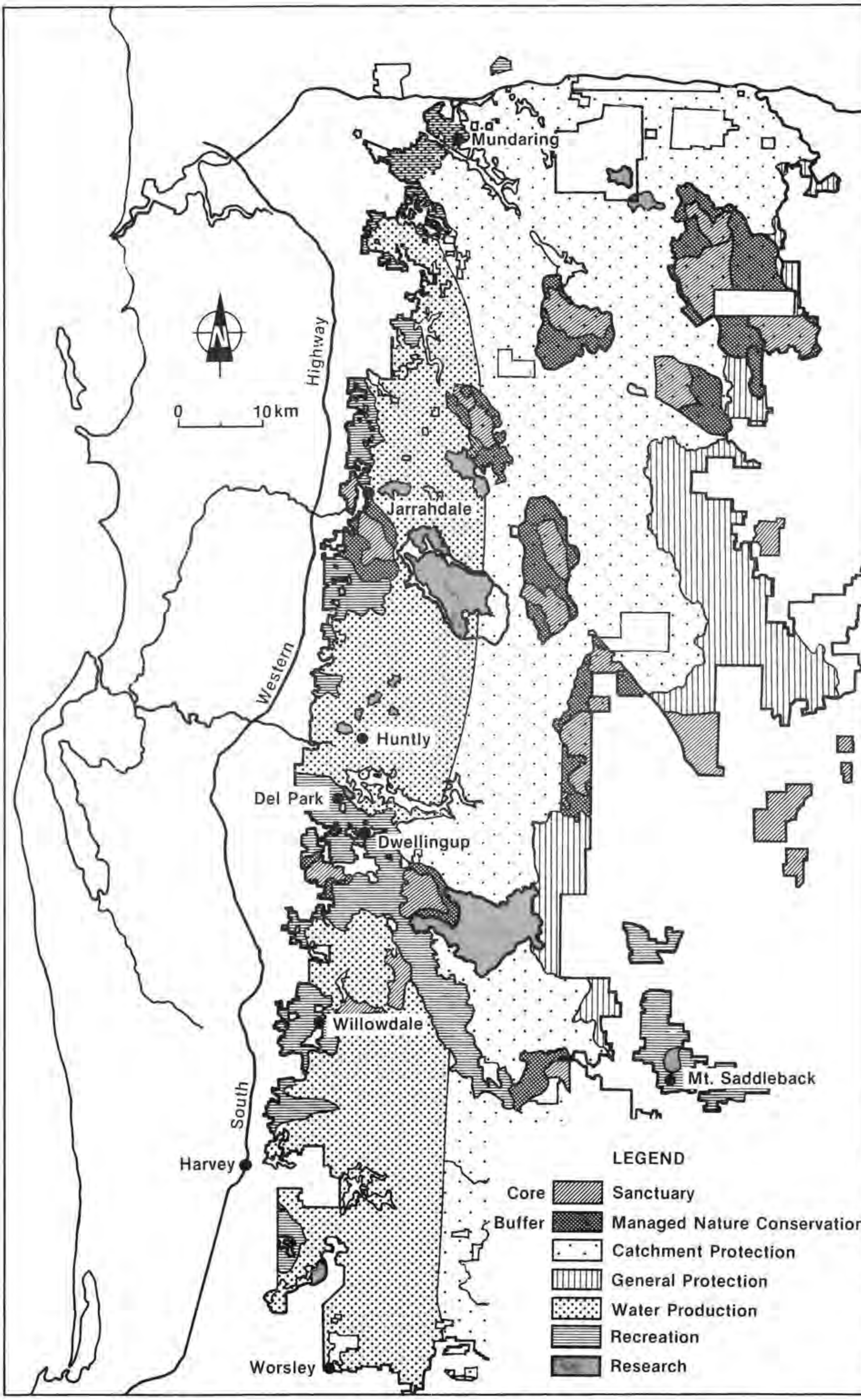

Figure 11. Current Management Priority Areas (Nov. 1983) in the northern jarrah forest

pendix C. Some variation in treatments is prescribed to cater for either the recreation or water production land use. These prescriptions represent a major advance as a statement of strategies for rehabilitation, and in the control of field operations. They are also an effective avenue for introducing new research results into operations.

In their Wagerup ERMP, Alcoa made a commitment to rehabilitate dieback affected areas adjacent to their mining operations. This commitment arose from the recognition that bauxite mining can lead to the spread and intensification of existing disease. Two measures have been adopted to meet this commitment. First, to minimise disease spread, rigorous hygiene provisions have been incorporated into all aspects of mining, from initial exploration to final rehabilitation. Second, to improve the forest outside minepits, the Forest Improvement and Rehabilitation Scheme (FIRS) has been developed, by which already infected areas are rehabilitated and uninfected areas are made more resistant. The FIRS operations are planned and carried out by the Forests Department using funds provided by Alcoa. Hygiene and FIRS prescriptions, analogous to the rehabilitation prescription, are used to guide these operations.

The development of the operational procedures detailed in the Rehabilitation and FIRS prescriptions is described in the following sections.

Development of minepit water control practices

Rehabilitation commences with treatments to establish soil physical conditions and topography such that the minepit becomes a stable non-eroding surface. Two major treatments are involved. First, ripping relieves the compaction of the minepit floor thus favouring infiltration of water. The operation can be done on the contour to promote infiltration by providing surface depression storage. Second, minepits are rendered into a form complete with banks, channels and sumps such that a stable water-holding or water-conducting system is created. The system is designed to cater for the surface water runoff that would arise from a 1 to 10 day storm event with a recurrence interval of 15 years.

Since 1978 major improvements have been made in the practice and understanding of these treatments. This has been combined with real and conceptual knowledge of soil hydrologic processes to develop models of minepit hydrology. Models have been progressively improved and can now be used to specify ripping and drainage design appropriate to any minepit.

Ripping and compaction

Studies of mining-induced compaction have been carried out by Alcoa in conjunction with the Civil Engineering Department, Western Australian Institute of Technology. In these studies the depth and degree of compaction and its variation with type of material has been defined. Depth of compaction has generally been found to be limited to 0.75 m.

In the past, all ripping has been carried out with a conventional chisel tyne to a nominal depth of 1.8 m. Investigation of the performance of this tyne followed observation that it was not achieving as good a fracture of the compacted layer as was desirable. This was at first ascribed to excessive soil water during ripping (i.e. to ripping after opening rains) but this has been largely discounted. The main problem was that the tyne had been operating below its 'critical depth' (i.e. the soil mass was deforming at depth with little lift and fracture). This led to the development of a 'winged' tyne designed for uplift of the soil mass. Tests on this tyne revealed superior soil fracture independent of soil water for no extra energy input over the chisel tyne. The winged tyne is now in operation.

Surface drainage

Up to 1981 the objective of minepit drainage was to detain all runoff within the minepit until it could be absorbed by infiltration. This method, though highly developed, has several deficiencies:

- it requires large water-holding structures, creating an undesirable terrain;
- it favours dieback by ponding water within the minepit and by contributing to seepage downslope from the minepit;
- it is not likely to be appropriate for use in the saline zone, due to the scope for salt mobilization.

It was therefore decided to pursue the development of a system designed to collect runoff with low profile banks, and to conduct it downslope on stabilized waterways to temporary sumps before discharge overland into streams. Some technical problems remain with water turbidity and soil and channel stability, but this method is expected to become the most widely used in future.

Mulching of the minepit surface

Studies during the mid-1970s, discussed in the last Steering Committee Report (Department of Industrial Development, 1978), examined the use of agricultural species and straw mulch for rapid stabilization of the pit surface and to minimize the turbidity of runoff. However, the risk of proliferation of agricultural plants from these sources has precluded their broad-scale use. The proliferation issue is being monitored. Woodchip mulch, on the other hand, offers the potential for immediate stabilization of bare surfaces without any weed hazard. Olsen (1980) found that a 3.5 cm deep woodchip mulch was sufficient for soil stabilization. It also enhanced the establishment of undersown native seed. Following from this study, woodchips under-seeded with native shrubs and ground-covers are now used extensively to stabilize batters, haul road verges and conveyor alignments on minesites.

Work currently in progress is examining the use of woodchips over rehabilitated minepits, not only to control erosion but also for possible benefits in hastening the return of invertebrate fauna.

Minepit hydrology and modelling

The practical development of ripping and drainage has been paralleled by an increasing understanding and quantification of minepit hydrology. The size of the various soil water storage sinks, and fluxes downward, laterally and upward have been given preliminary values. Current research aims to provide more detail and more accurate quantification of these processes, particularly their variation with soil water content, across minepit area, with ripping and drainage technique, and over time as vegetation becomes established.

Models are being progressively developed from these data. The current version (The Rehabilitation Earthworks Design Model) is sufficiently well advanced for operational use in specifying drainage design appropriate to either water infiltration or collection systems for any minepit (Croton and Tierney, 1983). In the model programme, the minepit is divided into a series of logical units (e.g. the area between two contour banks would be one unit) and a simple model is generated for each. These units are recombined to form the complete design model. This method permits a wide variety of minepit configurations to be modelled by a single programme. It readily allows incorporation of new data and can handle widely different rehabilitation procedures and objectives.

The model has been calibrated against a monitored minepit and found to give a good estimate of observed results (Croton and Tierney, 1983). Further validation work is planned. It is also planned to integrate this model with 'hillslope' models being developed to study the wider impact of mining.

Minepit revegetation

Understorey re-establishment and topsoil handling

Early work (Department of Industrial Development, 1978) established the advantage of spreading native seed to enhance understorey re-establishment. Such seed is now spread over all rehabilitated minepits as standard practice (Bartle *et al.*, 1978). Techniques for re-establishing understorey in pre-1977 minepits, where trees were established as plantations, are under investigation (Glossop, 1982).

Glossop (1980) and Glossop *et al.* (1982) also developed improved germination-stimulating treatments for native legume and eucalypt seed to enhance field germination of broadcast seed.

As an alternative or an adjunct to direct seeding of native shrub seed, topsoil handling methods have been investigated to see whether the natural seed load in topsoil can be utilized (Tacey and Glossop, 1980). Initial studies on topsoil handling compared stockpiling, direct return of the full 40 cm depth of topsoil, and 'double-stripping', where only the top 5 cm was removed and immediately re-spread, while the balance was stockpiled. Four years after these several treatments were applied, the advantages of double-stripping were clearly demonstrated by comparison of the range of understorey species which had established.

The above work has led to the implementation of double-stripping on an operational scale and in 1982 the top 5 cm were directly returned to approximately 50% of rehabilitated area within Alcoa's lease. For the remaining 50%, topsoil was stockpiled for varying periods before replacement. Double-stripping with direct return is not used where there is a risk of transferring dieback infected soil onto an uninfected site. Research is also being conducted into means of stockpiling topsoil without an irreversible fall in seed viability, nutrient levels or microbial activity. If such methods can be developed, they will eliminate problems of fresh topsoil shortages due to restrictions on moving dieback infected material.

More recent studies on the understorey have centred on investigating long-term successional trends in vegetation (Nichols and Michaelsen, in prep.). These studies should prove useful in predicting development processes in the rehabilitated ecosystem, and in avoiding problems which may otherwise develop.

Tree selection and establishment

Species selection

The identification of tree species suitable for rehabilitation has been given a high research priority. This is because the dominant native species, jarrah, is of limited use in rehabilitation due to its susceptibility to dieback. Jarrah is well adapted to its environment and finding other species to emulate its performance, particularly with respect to water and salt balances, may be difficult (Bartle and Shea, 1978).

Species selection has been based on the following criteria which indicate likely survival and production potential of introduced species in the northern jarrah forest environment:

(i) Tolerance to *Phytophthora cinnamomi*, fire and salinity.

(ii) Good timber.

(iii) Satisfactory performance in past minepit plantings and elsewhere in the northern jarrah forest, especially on sites with a naturally truncated profile (topsoil over clay). For example, *E. wandoo* occurs naturally on a profile type very similar to that artificially created in minepits.

(iv) Capacity to develop into a forest able to prevent long-term rise in groundwater and stream salinity.

(v) Aesthetic, honey and other values.

Current species use has been decided by rating prospective species according to these criteria. This has been done using all available sources of information, including performance in their native habitat, formal evaluation of growth locally (Hart 1976) and informal observation of local performance. There is currently no single species with proven capacity to satisfy all these criteria, though in current mining areas criterion (iv) above can be ignored due to the absence of any salinity risk. The currently used species are:

E. wandoo *E. laeliae* *E. accedens* *E. resinifera* *E. maculata*	Planted in high freely draining minepit areas.
E. patens *E. saligna* *E. calophylla*	Planted in low moist minepit areas.
E. patens *E. megacarpa* *E. rudis*	Planted in minepit sumps and wet areas.

To facilitate more systematic evaluation of species potential than is possible from assorted trial and operational plantings, a series of five major arboreta was established over the period 1976-79. These arboreta contain a comprehensive selection of some 70 eucalypt species with an average of two provenances per species (see Appendix B) all chosen for their potential to meet the selection criteria. Replicate arboreta have been established on all major disturbance site types (Table 4). These sites include types representative of disease degraded forest adjacent to minepits, both in high and low rainfall zones, and will therefore aid in species selection for FIRS plantings. Species plots are sufficiently large (greater than 0.5 ha per species) to minimize edge effects due to subsurface water movement and so will be suited to the study of hydrologic performance.

These arboreta are being monitored for canopy area development by low level aerial photography. Some detailed studies of growth and water relations have been carried out in the Del Park arboretum. This has resulted in the selection of two species (*E. wandoo* and *E. resinifera*) for a more detailed examination of water relations using the ventilated chamber technique.

A series of small arboreta have been established in agricultural land along the Hotham Valley (800-400 mm rainfall) by CSIRO. In this study, growth and transpiration is being assessed with a view to identifying species suited to salinity control in agricultural land. Up to age 27 months, the best rates of transpiration were recorded from *E. globulus*, *E. cladocalyx* and *E. wandoo* (Greenwood and Beresford, 1979). The strength of the *E. globulus* performance

Table 4 . Species evaluation arboreta

Location	Site Type	Planting Year	Area (ha)	No. Species
Del Park	1250 mm rainfall, bauxite minepit	1976	35	35
Marrinup	1250 mm rainfall, upland site with dieback disease	1978	80	70
George A	800 mm rainfall, lowland site with dieback disease	1979-80	70	70
George B	800 mm rainfall, upland site but no dieback disease	1979-80	80	70
Stene	725 mm rainfall, lowland site developed for agriculture	1979	80	80

came from its rapid leaf area growth whereas *E. wandoo* had superior transpiration per unit leaf area. *E. cladocalyx* was relatively good in both parameters.

Provenance trials

E. wandoo, E. resinifera and *E. maculata* are the major currently used species in rehabilitation and it appears likely that they will be used to some extent in the long term. Study of the variation within these species has therefore been commenced, with a view to identifying the best suited provenances.

A major collection of *E. wandoo* families was carried out by the Forests Department in 1981. A trial to examine the variation in the 125 seed lots collected was established at Jarrahdale in 1982. A less detailed trial looking at 42 of these lots was established at Del Park in 1983. In 1981 Alcoa commissioned CSIRO to make seed collections of *E. maculata* and *E. resinifera*. These have been included in provenance testing trials conducted by the Forests Department.

Tissue culture

The cloning of selected parent trees by tissue culture methods was commenced by Murdoch University in 1980. Trees displaying, or likely to display, particular desirable traits, such as good form and resistance to dieback, were selected. For example, naturally occurring hydrids of *E. marginata* x *E. patens* were sought as they may combine desirable jarrah characteristics with good dieback resistance. Field trials of cloned stock commenced in 1983.

A major CSIRO/Alcoa tissue culture project commenced in 1982. Seedlings from tissue cultures of salt resistant *E. camaldulensis* have been planted in field trials in agricultural land affected by salinity.

Seedling establishment

Tree establishment has generally been by hand planting of 6-month-old nursery seedlings at a density of 625 seedlings per hectare (4 m x 4 m spacing). However, trials in the past have indicated that trees also readily establish from broadcast seed (Bartle *et al.*, 1978). A difficulty with direct seeding of eucalypts is in getting suitable seedling spacing. During 1980-81 several plots were planted using a machine to regulate seeding rate. Though promising, the machine proved impractical on the minepit terrain. Additional spot sowing trials are scheduled.

Since 1981 a small quantity of tree seed has been included in the understorey seed mix to provide an operational scale contrast of the two modes of tree establishment and to provide an opportunity for jarrah to establish in the rehabilitated areas.

Plant nutrition

Jarrah forest soils are low in fertility and the loss of organic matter during mining further depletes scarce nutrient resources. In spite of this, nutrient research has until recently taken second place to more pressing soil physical problems. Furthermore, fertilizer use has been deliberately moderate due to the possibility of weed proliferation, contamination of water supplies and excessively vigorous growth leading to drought stress or disease.

Initial research looked at providing sufficient nutrients for tree establishment. This demonstrated the importance of nitrogen and phosphorus for growth and survival (Ward, 1983). Present practice consists of a spot application of 200 gm monoammonium phosphate per tree in a split application of 3 and 9 weeks after planting. In his review, Ward (1983) questioned the value of splitting the application. Since 1977, when a broadcast-seeded legume understorey was added to revegetation practice, 500 kg/ha of superphosphate was included as a broadcast dressing to improve legume growth. This rate was chosen subjectively. These combined spot and broadcast applications are successful up to age 6 years, but there is no information on responses to a wider range of inputs over a longer term to give confidence that it is the best treatment.

For this reason two major fertilizer trials were established in 1983. The first aims to define the response of trees to phosphate in the absence of other limiting nutrients. The second aims to determine whether any other nutrients, in addition to nitrogen and phosphate, give responses. These trials will be located in a minepit rehabilitated by the prescribed method, including legume understorey. They will be used as a source of tissue samples to provide nutrient standards for diagnostic tissue analysis, and will also provide a basis for upgrading current practice.

Development of FIRS prescription

Two categories of Forest Improvement Rehabilitation Scheme (FIRS) treatments have been developed. The first is to rehabilitate areas suffering high disease impact. The second is to improve disease resistance and vigour in dieback free or low disease impact forest. In both cases the overall objective is to increase the capacity of the land to support its long-term land use and, more specifically, to reverse or minimize the effects of dieback. About 2500 ha of each category have been treated under FIRS since its inception.

Treatment of high impact sites consists of salvage of marketable trees, retention of young dieback tolerant species and disposal of dead and degraded trees by heaping and burning. Revegetation with native understorey and tree species is then carried out. Trees are mainly planted in clumps around ashbeds or other favourable sites.

In the dieback free or low impact forest, the treatment consists of banksia elimination, burning to favour legume regeneration and thinning of overstorey to encourage tree vigour, and upgrading drainage from roads and minepits to minimise disease potential.

The FIRS treatments are in an early stage of development. Little research effort has been committed directly to design and evaluation of the treatments. Rather, FIRS can be seen as a synthesis of current knowledge from all sources of dieback and rehabilitation research.

Chapter 5

The Observed Changes Following Bauxite Mining and Rehabilitation

Hydrological response

Surface hydrologic response

Three research catchments established by the Metropolitan Water Board in 1966 have been used to evaluate the effect of bauxite mining and rehabilitation on the surface hydrologic response. These catchments are More Seldom Seen, Seldom Seen and Waterfall Gully (Figure 12).

Details of the hydrologic analyses involved are presented by Loh *et al.* (1984). Only the general results are presented here.

More Seldom Seen and Seldom Seen catchments have been extensively cleared, mined and rehabilitated over the last 13 to 15 years (see Figure 13) while Waterfall Gully has been subject to normal forest operations over the same period.

Annual water yield

Three methods of identifying changes in the annual streamflow volumes of the mined catchments relative to Waterfall Gully catchment were used, namely double mass curve analysis, statistical testing of the differences in annual flow volumes and nonlinear monthly rainfall-streamflow simulation. While all methods had some limitations and provided different estimates, the results showed that average increases of approximately 50 to 75 mm, or 20% to 30% of pre-mining flows, have occurred on the mined catchments over the period studied.

Figure 13 shows one estimate of the increase in streamflow volume on both More Seldom Seen and Seldom Seen Creeks and clearly indicates the time trend of increasing water yield.

The magnitude of the yield increases were significantly correlated with the total areas cleared/mined (Figure 13) and there was evidence that the increases tended to be larger in the wetter years. The best correlations with the level of clearing and mining occurred when the increases in yield were expressed as a percentage of the pre-mining streamflow.

While some 38% of More Seldom Seen catchment and 27% of Seldom Seen catchment had been cleared or mined by 1980/81, only 21% and 17% of the catchments had been reforested. At this time the reforested stands had reached average ages of about 5 and 6 years respectively. As a higher percentage of the catchment becomes reforested and the age of the rehabilitation stands increases, streamflow yields are expected to decrease. However, a much longer period of regeneration and a more detailed analysis is required before the role of rehabilitation in re-establishing the water balance can be reliably determined.

Flow components

It is important to know how the components of streamflow are affected by bauxite mining. For example, if the major increase in streamflow yield occurs in the groundwater component, then serious salinity problems could develop if mining operations move into areas of high subsoil salt storage. Alternatively, if most of the increase occurs at high flows during storm events, then erosion and sediment load potential would be greatly enhanced.

From analysis of the catchments described above, summer low flows (i.e. groundwater discharge) were found to increase for the mined catchments relative to the control catchment. These increases were in similar proportion to the annual streamflow increases.

The flood response of the three catchments were studied by comparing the instantaneous yearly peak flows over the period of record. The peak flow rates of the two mined catchments increased between two and three times relative to Waterfall Gully.

Inspection of selected hydrographs shows that the major portion of the streamflow subsequent to mining retains the characteristic sluggish recession typical of forested catchments. This implies that the increase in yield occurs largely during the winter period when shallow seepage from the lateritic soils is the dominant source of streamflow.

Stream salinity

Regular sampling for chloride ion concentration has been carried out for the three research catchments since 1966. Over the period of study, no increase in salt concentration was detected. This is to be expected in view of the low concentration of ground-

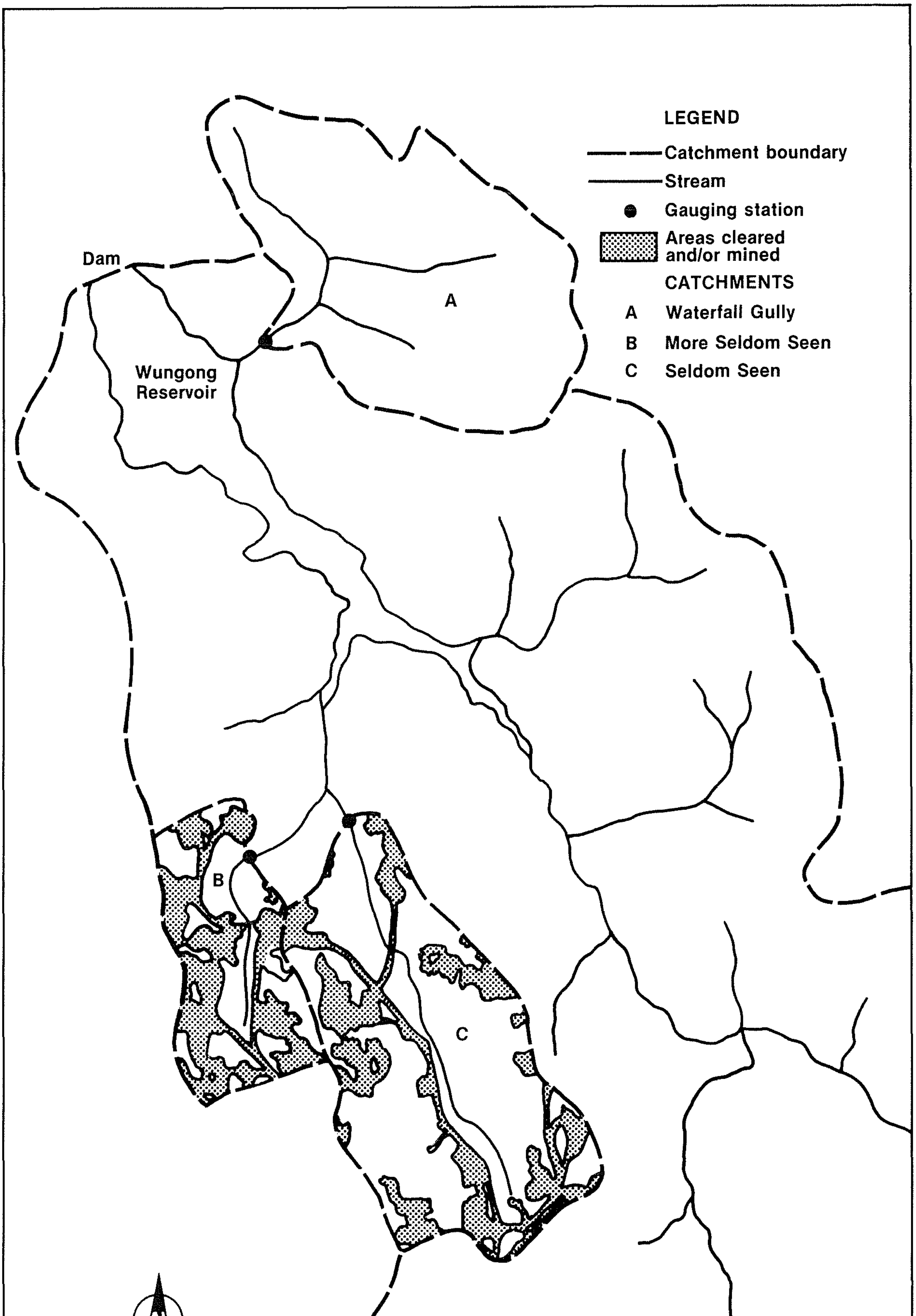

Figure 12. Locations of Waterfall Gully, Seldom Seen and More Seldom Seen catchments showing areas cleared and/or mined

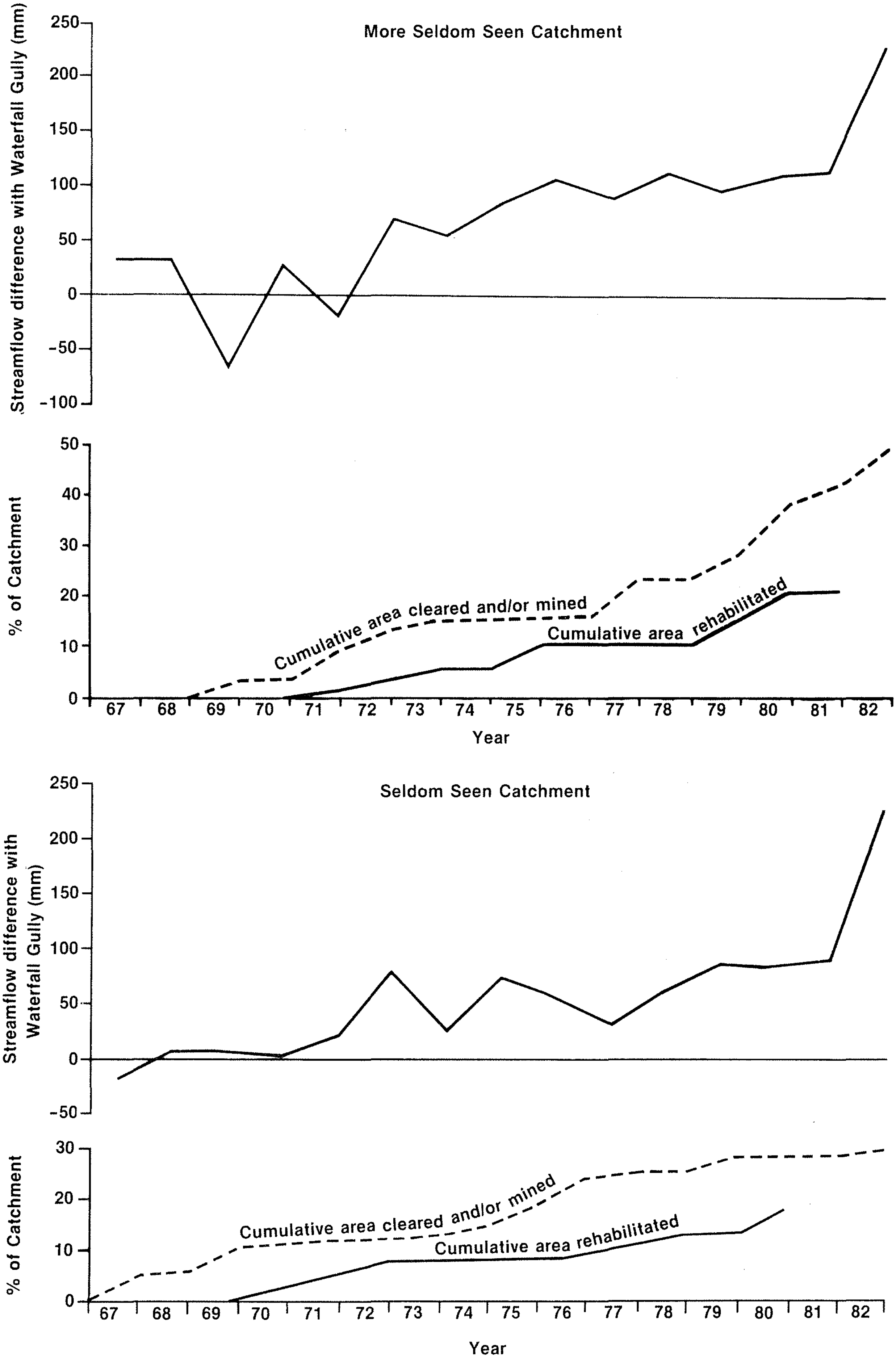

Figure 13. Changes in annual streamflow relative to Waterfall Gully and their relation to clearing, mining and rehabilitation in Seldom Seen and More Seldom Seen catchments

water salinity for these catchments (approx. 180 mg/L TSS).

As regards salt load, increases of the output to input ratios of Seldom Seen and More Seldom Seen catchments, relative to Waterfall Gully, are apparent. This reflects the increased streamflow following bauxite mining, since the stream salt concentrations remained virtually constant.

Groundwater response

In 1974 a detailed groundwater monitoring programme was initiated by CSIRO on Del Park catchment (a small tributary of the South Dandalup River). Clearing operations began in 1975/76 in preparation for the mining of two of the three ore bodies in the catchment over the following three years. In addition to this programme, a number of sites were established to monitor groundwater beneath existing mined pits and to monitor longer term changes through a pre- and post-mining phase. These two programmes form the basis for evaluating the effects of bauxite mining on groundwater response.

Piezometric levels

In general the net yearly changes in groundwater piezometric levels have been difficult to attribute unambiguously to bauxite mining. Most of the observed changes have been within the range of responses of forested sites. However, increasing piezometric levels downslope of pits were identified at two locations and these are at least 0.2 m/year. Peck (1983) analysed the change in minimum piezometric elevations from 1975 to 1981 for two groups of bores on Del Park catchment — one group affected by mining (14 bores) and the other in forest (20 bores). Over the six year period a net relative increase of 2.0 metres was calculated between the mean of the bores affected by mining and the mean of the bores which remained under forest. Hurle and Associates (1983), in analysing the Del Park results, found no clear definition of the significance of bauxite mining in causing annual groundwater level changes. Three limitations of the study were noted, namely that the control area was significantly disturbed by logging, that equal weight was assigned to each bore regardless of its position in the landscape and that the number of observations of mined areas were reduced during the mining period of 1976-77. Additionally, some concern exists about the interdependence of observations from one groundwater body. To add to the difficulties of the groundwater programme, the years of most intensive monitoring covered a period of below average rainfall.

As regards seasonal response to winter rainfall, the observations suffer the same problems as the long-term trends discussed above, thus precluding the accurate differentiation between bauxite mining and natural seasonal effects. On the Del Park catchment, seasonal rises in piezometric levels were generally less than one metre in 1975 and 1976. From 1977, following bauxite mining, significant increases in seasonal rises were recorded all over the catchment, including the 'undisturbed' eastern portion. Variability from bore to bore within the mined areas was large, so seasonal variations could not be directly attributed to bauxite mining. At sites downslope of minepits there is evidence of a longer period of groundwater recharge following mining. This is thought to result from an increase in the duration of the perched shallow aquifer which forms in the lower mid-slope areas below minepits.

In summary, bauxite mining appears to have disturbed piezometric levels of groundwater both within but particularly downslope of the actual pits mined. However, these disturbances are small relative to natural variations in the undisturbed forest and are certainly less marked than changes caused by agricultural clearing (Peck, 1983).

Groundwater salinity

Martin (1982) reviewed the groundwater salinity variations from both forested and mined locations. Undisturbed forested sites tended to show a slight decrease in salinity of about 16 mg/L TSS per year from 1975-80. In contrast, at minesites both within the minepits and in the adjacent forest, either no change or a slight increase in groundwater salinity has occurred.

Forest response

Tree growth in minepits

Height and leaf area growth are sensitive indicators of a tree's adaptation to its site, and provide criteria by which to evaluate performance. Generally, early height and leaf growth of minepit plantings has been good, but there is evidence that this good growth may not be maintained as trees grow older. Figure 14 shows the results of monitoring height growth annually in three species planted in minepits in 1971. Early growth of *E. globulus* and *E. agglomerata*

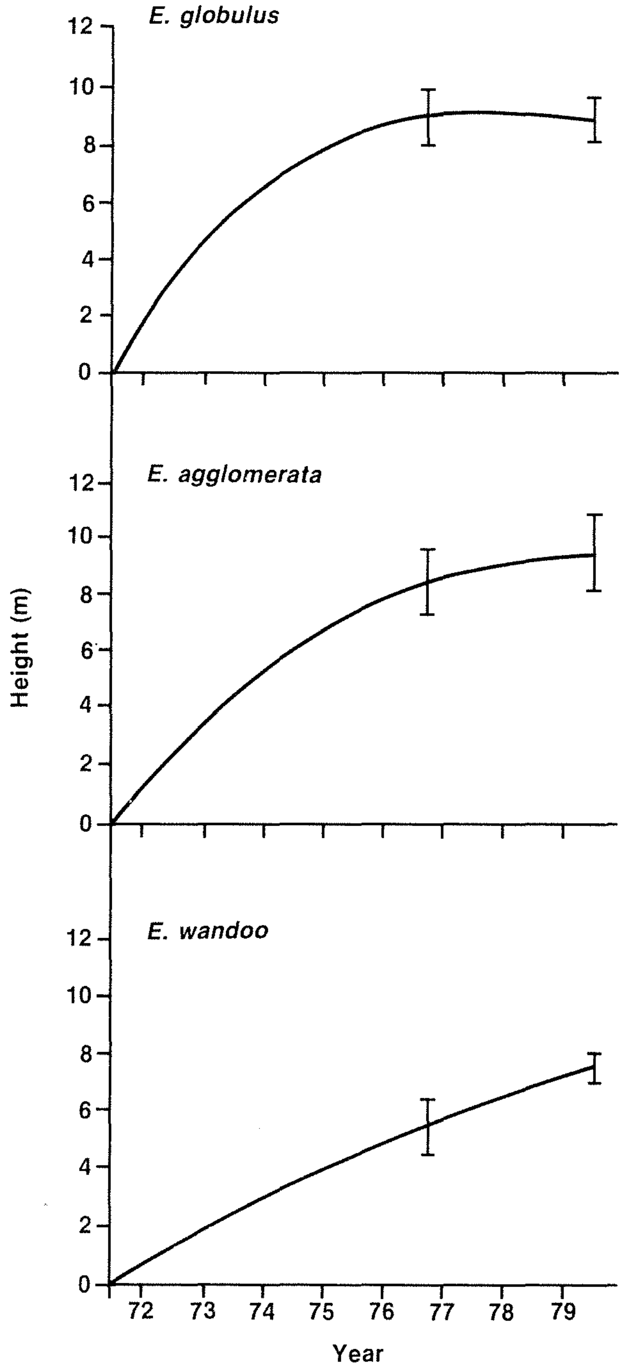

Figure 14. Tree growth performance in rehabilitated minepit plantations established in 1971

was very rapid but suffered a steep decline in rate from 3 to 8 years, whereas *E. wandoo* was initially slow to establish but maintained nearly linear growth between years 3 to 8. The *E. wandoo* pattern is more promising. These observations are specific to the rehabilitation standards of 1971. Improved ripping and nutrition in later rehabilitation will have considerably altered growth potential.

Root growth in minepits

Observations of jarrah root growth reveal that it is able to exploit the whole weathered profile and that access to the profile is facilitated by a system of vertical root channels (Dell *et al.*, 1983). The profile is very deep (up to 40 m) and apparently quite inhospitable. Effectively tapping this difficult environment will have a major bearing on water uptake and success of rehabilitation. The reoccupation of the profile by roots therefore provides scope for evaluation to augment the above-ground observations of growth.

Early work outlined by the Department of Industrial Development (1978) and by Dell *et al.* (1983), focused mainly on the role of ripping in overcoming the compaction of the minepit floor. Recent work has had the additional objective of determining which rehabilitation species are able to enter the root channel system in the deeper clay profile.

The only trial established to test the impact of variable ripping depth (0.3 m, 1.2 m and 2.0 m) on tree growth (five different species) was established at Jarrahdale in 1975. Tacey (1979) and Pickersgill (1982) reported no improvement in diameter or height growth with increased ripping depth on this trial. Subsequent excavation of the trial site revealed that up to 2.5 m of fill had been placed over the original pit floor during rehabilitation earthworks, placing the validity of the study in doubt.

Deep root occupation has been observed by excavation at several sites. This work was facilitated by the adoption of a method of excavation which reveals successive horizontal layers so that individual descending roots could be followed. This work has shown that most rehabilitation species have roots which pass through the ripped layer to occupy most of the old root channels to a depth of 3 metres (Alcoa 1981). Excavation beyond this depth has not yet been attempted since it presents considerable practical problems and difficulty in interpretation of results.

Transpiration

Carbon *et al.* (1981) showed that six- to eight-year-old stands of *E. microcorys* in bauxite pit plantations (without understorey) had nearly double the leaf area, and only some 20% less transpiration per unit leaf area, than adjacent jarrah forest overstorey. They concluded that these plantations in particular, and pit plantings in general, were unlikely to transpire less than native forest.

Subsequent work by Colquhoun *et al.*

(1984) indicates that other major rehabilitation species, namely *E. maculata*, *E. resinifera* and *E. saligna* are similar to *E. microcorys* in producing higher leaf area and lower per unit leaf area transpiration rates. However, they concluded that more detailed studies were required to reliably evaluate the transpiration potential of rehabilitation species.

The problem with the simple, extensive methods employed in these two studies is that they lack resolution, especially when being used to predict water balance over large areas. Quite small differences in performance between different species or rehabilitation methods may be of critical importance in rehabilitation in the intermediate zone, and yet not be detectable with crude measurement methods.

The ventilated chamber method was developed to provide a more refined measurement of transpiration. It is capable of directly measuring transpiration of whole trees (to 30 m) or small areas of understorey (to 10 m^2). Description of the design, development and applications of the method are given by Greenwood (1982), Bartle (1982) and Colquhoun *et al.* (1983).

Understorey in minepits

The current rehabilitation method rapidly produces a large understorey biomass. Though not yet fully documented, it is clear that this growth contributes to the success of rehabilitation in several fundamental ways.

Good ground cover is achieved within two years and a dense two metre tall thicket of shrubs can be created in four years. This affects the hydrology of the system by protecting the soil surface from erosion and by providing plant surface area for rainfall interception. A complete litter cover is obtained within four years, favouring fauna return and commencing the process of decay, generation of soil organic matter and nutrient cycling.

The understorey biomass, particularly when it reaches senescence at age 5-8 years, will present a major fire hazard to the trees which are at a very sensitive stage of growth. Mechanical and controlled burning techniques are being assessed for control of this hazard.

Ongoing minepit nutrition

The pre-1977 minepit plantings were established without understorey. Obvious signs of nutrient deficiency were apparent in these stands by 1979 and aerial fertilization was carried out. This stimulated a large response in height and leaf area growth in most species and locations. However, the response was not sustained and signs of deficiency re-appeared. The transient nature of the response and subsequent trials indicate that nitrogen is the major deficiency.

In contrast to the pre-1977 plantings, later plantings have a legume-based understorey. No deficiency symptoms have been observed in these stands, suggesting that nitrogen fixed by the legume understorey is being redistributed through the whole plant community. Work has commenced to describe this and other processes of nutrient cycling to determine if the ecosystem is self-sustaining with respect to nutrients.

Fauna

Fauna play a major role in the breakdown and redistribution of organic matter and nutrients, and are an essential part of any rehabilitation ecosystem. As such they provide another index of the success of rehabilitation and have attracted considerable research effort.

Surveys of vertebrate fauna have shown that a high proportion (70-90%) of bird, reptile, amphibian and mammal species present in the forest are also present in rehabilitated bauxite pits (Kabay and Nichols, 1980).

These surveys have been followed by intensive studies to define population densities, age structure and feeding habits. For example, bird populations in healthy and diseased forest compared with those in rehabilitated minepits with and without understorey are shown in Table 5 (Nichols and Watkins, in press). In density and diversity, the populations in minepits with understorey compare favourably with healthy forest.

The red-eared firetail finch and the carpet snake, both listed in the State "Rare, or otherwise in Need of Special Protection" list, are known to occur in current mining areas. They have been studied to determine what impact mining may have on them. Nichols *et al.* (1982) have shown that the red-eared firetail finch is not at risk since its habitat (stream zone vegetation) is not subject to mining.

In an initial study of invertebrate return to rehabilitated areas, transects were established on 28 minepits and 4 forest control sites. Extensive physical and biological data were recorded and specimens collected

Table 5. Avifaunal population survey

Population parameters	Healthy jarrah forest		Dieback affected forest		Rehabilitated area		
	1	2	3	4	5	6	7
Species density (per hectare)	13.2	12.6	6.0	13.5	6.9	0.2	12.0
Species richness	16	16	9	14	16	1	13
Diversity	1.09	1.08	0.88	0.99	1.08	—	0.96

Note: Sites 5 and 7 have understorey. Site 6 is an older area of tree plantation without understorey.

from all vegetation strata using a range of techniques. When complete, the analysis of these data should reveal major aspects of the ecology of a wide range of invertebrate groups. Findings for ants have been published by Majer *et al.* (in press), and for termites and collembola by Nichols and Bunn (1980), and Greenslade and Majer (1980).

These studies highlight the contrast between pre-1977 rehabilitation (without understorey) and later rehabilitation where understorey, and enhanced litter fall, provide a more attractive environment for invertebrates. As was observed for birds, the range of species found in such rehabilitated areas approaches native forest.

Later work has focused on the predatory invertebrates such as scorpions, spiders and centipedes which are higher in the food chain and indicate the stability of the populations of lower order invertebrates which support them. Preliminary results show substantial populations of these animals.

Forest adjacent to mined areas

There has been increased spread and intensification of dieback following mining, but this has not been as great as was at first feared. For example, Bartle (1976) classified most of the area downslope of minepits as 'at risk'. In the area he studied (the Seldom Seen Catchment) the area downslope of minepits was 61% of the catchment total, of which 28% of total area was severely dieback degraded when mining commenced. Since the commencement of mining in 1968, this area has expanded. Expansion consisted of general slow upslope spread around the perimeter of the infected area, and several areas of intense upslope disease developed on sites associated with surface or shallow subsurface water accumulation (downslope of minepit sumps or haul-road drains). This strong dependence of upper slope disease on impeded drainage also occurs in undisturbed situations (Shea *et al.*, 1982). Since disease may be very site-specific, it suggests that Bartle's (1976) inference of uniform loss downslope from minepits is pessimistic. It is not possible to precisely specify the extent to which mining will exacerbate dieback. However, it is clear that mining can cause the spread and intensification of disease and that this may put substantial areas of forests at risk where there is little pre-existing disease.

The aim of the Forest Improvement and Rehabilitation Scheme (FIRS) is to rehabilitate old infected areas and to minimize any disease impact in uninfected or lightly infected areas. The scheme started in 1979. Problems with some aspects of establishment methods are apparent. For example, trees planted on some high impact sites with impeded subsoil drainage are not thriving; legume regeneration and banksia kill has been variable; some disease deaths in retained jarrah have occurred. However, overall results in terms of vegetation response appear satisfactory. Rigorous evaluation of disease control and hydrologic impact has just commenced.

Chapter 6
Implications for Future Land Management

Water quantity and quality

Evidence to date from the observed changes in the hydrological response of several small catchments following bauxite mining and rehabilitation *in the high rainfall zone* may be summarised as follows:

- cumulative water yield increased by the order of 20% to 30% in the decade following mining;
- groundwater discharge increased approximately in proportion to the annual streamflow increase;
- peak streamflows increased;
- streamflow salinity remained unaffected due to the low soil salt storage and low groundwater salinity;
- salt load increased in proportion to the yield;
- groundwater piezometric surfaces may have risen (relative to unmined areas) by as much as two metres in six years following mining;
- groundwater salinities in mined and adjacent areas may have increased slightly relative to forested locations.

The above results are subject to uncertainties in the method of analysis and the finite number of observations, as described in the earlier sections of this report. Furthermore, the long-term impact of bauxite mining on the water resources of the high rainfall zone will require several more years of monitoring of rehabilitated catchments. However, assuming that the above conclusions are accurate, their consequences for the high rainfall and intermediate rainfall zones can be discussed.

In the high rainfall zone bauxite mining appears at present to be safe in regard to streamflow and salinity. In the water resource catchments there may be some economic benefit in increasing the yield, if this does not at the same time incur unacceptable risks of flooding or turbidity. The major problems still facing bauxite mining in the high rainfall zone are minepit surface water discharge and the spread of dieback. The current means of disposing of minepit surface water, termed the 'water retention method', aims to maximise water infiltration and evaporation over the whole minepit by the use of deep ripping and contour or grade banks. Excess water is transported down waterways and collected in a minepit 'sump'. The disposal of water from this sump still poses a problem because the minepit water is of too high turbidity for direct piping to streams and the alternative of allowing slow seepage down the hillslope increases the susceptibility of the forest to dieback.

In the intermediate zone the situation is more complex from the point of view of salinity risk, owing to the variability of soil salt storage and the presence or otherwise of a discharging groundwater system. In areas of high salt storage, the 'water retention method' of minepit water disposal may have adverse effects on stream salinity due to increased recharge to groundwater and the leaching of salts from the soil profile. This difficulty has prompted the consideration of a low infiltration method, in which deep ripping is excluded to minimise infiltration. Although this may go some way towards reducing salt leaching, the method introduces additional problems of vegetation establishment, soil erosion and increased minepit surface water (with its associated disposal problems).

To ascertain the safety of bauxite mining and rehabilitation in the intermediate zone, a much clearer understanding of its quantitative effect on specific hydrologic processes is required. This, along with catchment studies (with possible trial mining), will form the focus of future research (see pages 38-39). It may then be necessary to develop and evaluate further control procedures in the mining and rehabilitation operation. The success or otherwise of this work will have a strong bearing on the future of bauxite mining in the intermediate zone.

Dieback

No formal measurement of expansion of disease during mining and rehabilitation has been attempted, but observation shows that both spread and intensification of disease occurs. Its actual extent will depend on the success of practices to disfavour disease which are currently being developed. The prognosis for FIRS-treated forest on high impact sites, and for the bulk of minepit vegetation, is favourable. The success of revegetation or of disease prevention on high impact sites (i.e. those with impeded subsurface drainage) is uncertain. High impact sites will include those rendered vulnerable by mining-related disturbance to drainage, as well as those naturally vulnerable.

This position is tolerable in current mining areas in the high rainfall zone. Where a water production land use priority exists, any shortcoming in the success of revegetation will favour water yield and is unlikely to compromise water quality. Where a recreation land use priority exists, areas of sparse tree cover are not necessarily a disadvantage. However, the position will not be acceptable in catchment protection MPAs. Research must continue to develop rehabilitation methods which will prevent salinisation. Most importantly, a capacity to identify and treat high impact sites must be developed.

Landscape and recreation

Together, FIRS and minepit rehabilitation are a whole landscape treatment projected to be carried out over much of the non-saline forest zone in the next three to five decades. Considerable expenditure will be made on these works. The scale and intensity of this activity suggests that there is scope to cater for landscape aesthetic and recreation values to an extent not usually possible.

On the 'micro' scale, development of these values is generally well advanced. For example, large expenditure is incurred in landscaping minepits. Minepit terrain and the density of large boulders is regulated with aesthetics in mind and an 'aesthetic' seed mix is provided for planting high visibility locations such as road verges.

On the 'macro' scale, the allocation of land uses has given due consideration to landscape and recreation, but the realisation of the full potential of these values during rehabilitation has been limited by the absence of detailed landscape analysis and planning. Generally, little attempt has been made to integrate good micro-scale work into whole planned landscapes including full utilisation of existing natural features. Retention of selected vistas, blending of minepits into adjacent forest, avoidance of repetitive, artificial patterns and numerous other landscaping practices could be adopted. One pilot integrated plan, in the Marrinup recreation MPA, has been carried out. There is scope for major research and operational effort in this field, particularly in the areas where mining has just commenced (Willowdale and Mt Saddleback). The publication of the Forests Department's Northern Region Recreation Framework Plan (Forests Department, 1983) should now enable a more systematic approach to this problem.

Ongoing management and silviculture

Considering the large area that will be treated in future years, a complete range of management and silvicultural practices should be developed for the post-mining forests. In the case of forests adjoining the minepits, existing knowledge and practices could be readily adapted. In minepits, completely new practices must be developed. These two contrasting land types must also be integrated into a coherent management framework.

Fire control is one of the major problems which must be addressed in the short term. Varying rates and types of fuel accumulation, the dispersion of fire-tender saplings (and possibly some fire- susceptible species) across the landscape, and the intermingling of contrasting minepits and FIRS areas, will all make fire management a more complex and costly operation. Preliminary estimates suggest a temporary five-fold increase in fire control costs, for at least the period of fire vulnerability of young trees (one to two decades).

The fire ecology of revegetated areas also needs consideration. Particularly in minepits, the effects of fire on nutrient cycling and understorey composition must be determined. The vulnerability of new ecosystems to wildfire should also be ascertained. Other medium to long-term management and silvicultural problems include the manipulation of stand density to favour tree health, timber production and water yield; the possible need for ongoing fertiliser inputs; and maintenance of drainage systems.

In the long term new timber harvesting and utilisation problems must be solved. At this time, methods of regeneration of the stand will also need to be developed. All of these operations will need to be carried out in the ecologically more diverse forest than the original one. This will make management more complex.

Chapter 7

Priorities for Future Research

Hydrological studies

Bauxite mining in the high rainfall zone of the jarrah forest is now regarded as being safe with respect to stream salinity, owing to the low soil and groundwater salt concentrations. There are, however, significant problems related to minepit water control and dieback spread downslope of minepits yet to be solved.

The major emphasis of future research is to address the problems of mining in the intermediate and low rainfall zones, where potential salinity hazards are much greater. One conclusion of this report is that a clearer understanding of the general forest hydrological processes and the effect of mining on them is essential. Future research requires an upgrading of studies in the area where mining is currently taking place, in addition to the establishment of new research sites in the intermediate zone.

The main objective of the hydrological research programme may be summarised as follows:

to quantify the effects and consequences of a range of bauxite mining, rehabilitation and forest management practices on the quality, quantity and variability of the water resources of the region, especially the intermediate rainfall zone.

The specific research tasks have been categorised into three areas, namely minesite water studies, hillslope studies and small catchment studies.

(i) *Minesite water studies*

The clearing, mining and rehabilitation procedure itself comprises a major disturbance to the forest hydrological cycle. As such, research emphasis should be placed on determining the most appropriate procedure for any given situation. The high priority research tasks are discussed below:

- *Minepit water disposal:* A suitable method is required to dispose of excess surface water from minepits without seriously affecting stream turbidity, spreading or intensifying dieback or accentuating downstream flooding. One approach to be investigated is the 'vegetation filter' which may absorb particulate matter from minepit runoff.
- *Infiltration and groundwater recharge*: Appropriate methods of minepit floor treatment are necessary in the light of potentially conflicting objectives. It is essential to rip the clay pit floor to allow seedlings to sink their roots into old root channels (which become sealed during the bauxite excavation). However, the reopening of root channels will facilitate deep percolation and groundwater recharge which, in the eastern areas, could give rise to the potential for salt mobilisation. On the other hand, if the minepit floors are not ripped, the soil may only support heath vegetation and additionally surface runoff will increase. These conflicting strategies need to be resolved.
- *Evapotranspiration*: Measurement of evapotranspiration from native forest and rehabilitated minepits is necessary to determine the short-term and long-term effects of altering this major hydrological component. Further development and application of appropriate techniques remain a priority in this respect. More intensive study by short-term/ small-scale methods, such as the now highly developed ventilated chamber, will be essential to determine the processes by which rehabilitation species regulate water consumption. From this work appropriate plant communities could be specified. Longer-term/larger-scale methods will be required to confirm that the specified plant communities do establish the required water balance.

(ii) *Hillslope studies*

There has been a growing realisation that bauxite mining not only affects the immediate areas mined but also the adjacent slopes and to some extent whole catchment areas. Furthermore, it is being appreciated that the study of individual processes or problems in isolation is not always as appropriate as the system study approach. For these reasons a new research impetus is being made in an attempt to quantify hydrological processes and to obtain water and salt budgets for the pre-mining, mining and rehabilitation phases, at the hillslope scale. At this scale almost all the processes are present, yet the system is not too large to involve hopelessly time-consuming data retrieval and processing. The major outcome of this study will be an evaluation of the disturbance of bauxite mining and rehabilitation to individual hydrologic processes, and their consequent effect on salt mobilisation, dieback susceptibility and stormflow. It will be necessary to locate at least one study in the high rainfall zone and at least two in the intermediate zone on potential trial mining catchments.

Specific hillslope studies will include:

- *Water and solute balances*: An important part of the study is to quantify the water movement in its different pathways, in other words to measure the separate components of the hillslope hydrological cycle. The major components to be measured are rainfall, evapotranspiration, soil water storage, groundwater recharge and groundwater outflow. An almost parallel set of measurements is required to quantify the various components of the salt balance. These measurements will be necessary throughout pre-mining, mining and rehabilitation phases.
- *Streamflow generation*: In relation to streamflow quantity, quality and storm response, it is necessary to determine and quantify the mechanisms of streamflow generation. In the undisturbed forest the major streamflow component is interflow while peak flows are produced by runoff from small saturated source areas. The effects of bauxite mining and rehabilitation on these mechanisms must be evaluated.
- *Computer models*: The importance of computer modelling will be to increase the conceptual understanding of system behaviour and of component interactions, and to identify deficiencies in current research. In addition, it will improve the ability to extend the results from necessarily few localised, but detailed, field studies to bauxite mining over a large region.

(iii) *Small catchment studies*

Small catchments are the appropriate scale for assessing the net effects of mining and rehabilitation for management purposes since, in the long term, water and salt discharge is of prime concern. Additionally, catchments incorporate some factors which are not easily considered at the hillslope scale, for example, topographical convergence, saturated source areas and groundwater discharge. Moreover the integrated catchment response may differ to that predicted from hillslope process studies.

Some of the effects of bauxite mining and rehabilitation on catchment response in the high rainfall zone have been described in Chapter 5. These studies, although indicative of general effects, suffered problems of inadequate pre-treatment data and of being too large for detailed scientific study. For these reasons, and also because the response to land use changes are observed more quickly in the high rainfall zone, it is intended to study the consequences of bauxite mining and rehabilitation on at least one small catchment in the high rainfall zone.

However, the primary task of future research is to establish experimental catchments in the intermediate zone. These catchments should, amongst other things, be suitable for trial mining. The specific priority tasks to be carried out on these catchments are:

- *Streamflow response*: To determine the effects of bauxite mining and rehabilitation on streamflow quantity, quality and storm response in the intermediate zone, it will be necessary to install gauging and sampling stations on each catchment several years prior to treatment.
- *Groundwater response*: Similarly, to assess the effects of mining and rehabilitation on groundwater, it will be essential to install an appropriate array of deep piezometers several years prior to treatment. The recharge to groundwater may be inferred from net changes in piezometric levels.
- *Streamflow components*: An important part of the catchment study is to measure pre- and post-mining groundwater discharge to streamflow. Increased discharge of saline groundwater is thought to be the major threat to stream salinity in the intermediate zone.

Forestry and management studies

In the past several years there have been major advances in the technique and management of minepit rehabilitation. This has led to increasing confidence in the long-term viability of the minepit ecosystem. Improved ripping and drainage control has resulted in a stable minepit surface. Minepit vegetation is diverse, healthy and vigorous;

it is forming litter, attracting soil micro-fauna and forming soil organic matter. However, rehabilitation and disease protection in areas downslope of minepits and roads is not yet well advanced and the design of minepit hydrology to disfavour downslope disease is at an early stage.

The possible future extension of bauxite mining into the intermediate rainfall zone, where salinity is of concern and where the land use priority changes to catchment protection, presents many new problems for rehabilitation. These problems must be addressed in the short and medium term so that suitable rehabilitation methods are available for trial mining by about 1990. In this zone the hydrology and disease aspects of rehabilitation become critical.

The overall objective of rehabilitation research is to design a range of forest ecosystems adapted to specific sites (minepits and adjacent forest) and appropriate to specific uses (water production, recreation and catchment protection). This design task can be considered at three levels. First, there is the development of soil physical, soil chemical and biological treatments of rehabilitation. Second, there is the integration of these treatments into whole ecosystems on particular sites. Third, there is the integration of these particular sites into whole landscapes and catchments which are able to perform as required. An aspect of this performance may include the need for some ongoing management input.

The research required to guide rehabilitation design must inevitably be closely coordinated with the hydrologic research already discussed, and with dieback research. This listing of major research tasks for each of the levels of design is oriented around the biological aspects of rehabilitation.

(i) *Development of rehabilitation treatments*

- *Rehabilitation of high dieback impact sites*: Impeded drainage appears to be a major contributing factor to the high disease status of these sites. The study of physical treatments (e.g. ripping or blasting) to alleviate this and allow more vigorous vegetation to be established is necessary.
- *Nutrition in rehabilitation*: Nutrient inputs to rehabilitation stands in both minepits and dieback forest have deliberately been limited. Evaluation of the factors for and against this policy must be undertaken.
- *Biological potential of rehabilitation species*: It is necessary to continue to evaluate the potential performance of major rehabilitation species. Important attributes are evapotranspiration, disease and fire tolerance, growth rates and production, and ease of management. Also, it is important to commence the evaluation of specialized vegetation such as heath for 'low infiltration' rehabilitation, species adapted to drainage channels (which give good stabilization), and species for vegetation filters to counter turbidity.
- *Protecting/augmenting vegetation of high dieback impact sites*: If a capacity to predict the location of high disease impact sites (either natural or disturbance prone) can be developed then methods for protecting or augmenting this vegetation cover should be evaluated.

(ii) *Integration of treatments into ecosystems*

The treatments imposed in rehabilitation interact to produce a whole ecosystem. It is not readily apparent just what contribution a particular treatment makes to the system as a whole. Some understanding of the sensitivity of rehabilitation ecosystems to variation in the input treatments is therefore necessary so that ecosystems with particular properties can be specified. Physical trials to establish the inter-relationships of treatments will be required for this purpose.

(iii) *Integration of site ecosystems into whole landscapes*

Minepits and adjacent forest must have rehabilitation ecosystems which are compatible, that is, which together reconstitute whole landscapes or catchments able to meet the land use objectives. This point is especially important with ecological processes which may extend widely across the landscape, such as hydrology, disease and fire, and also with management factors such as access and aesthetics. Research on the hillslope or small catchment scale will be required to determine the compatibility of particular site ecosystems.

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Appendix A

MEMBERS OF THE STEERING COMMITTEE FOR RESEARCH ON LAND USE AND WATER SUPPLY

Chairman

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Mr K.L. Barrett,	Public Works Department
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Mr M.L. Poole,	Department of Agriculture
Mr G.C. Slessar,	Alcoa of Australia

Secretary

Mrs L.T. Berson, Department of Conservation and Environment

Appendix B

TREE SPECIES PLANTED IN ARBORETA 1978-80

E. marginata
calophylla
patens
laeliae
megacarpa
gomphocephala
rudis
wandoo
accedens
astringens
gardneri
falcata
kondininensis
loxophleba
sargentii
spathulata
platypus
lehmanii
occidentalis
salmonophloia
salubris
oleosa
longicornis

E. flocktoniae
transcontinentalis
griffithsii
aromophloia
dives
goniocalyx
macrorhyncha
mannifera
radiata
viminalis
rubida
huberana
baxteri
cladocalyx
leucoxylon
odorata
largiflorens
woolsiana
microcarpa
albens
melliodora
polyanthemos
sideroxylon

E. fasciculosa
moluccana
robusta
botryoides
paniculata
bosistoana
resinifera
maculata
thozetiana
ocrophloia
crebra
melanophloia
drepanophylla
decorticans
citriodora
camaldulensis
globulus
saligna
microtheca
intertexta

Pinus pinaster
Pinus radiata

Appendix C

"REHAB 84"

PRESCRIPTION FOR REHABILITATION OF BAUXITE MINES IN THE WESTERN JARRAH FOREST

1. INTRODUCTION

1.1 Environmental aspects of bauxite mine planning, operations and rehabilitation in the western jarrah forest are complex. Overlapping tenures and legislation are involved, together with interactions between land use and biological factors.

1.2 However, the complexity of the system must not deter the formulation and clear statement of objectives, strategies and most up-to-date techniques. This statement can then provide an agreed basis for review and up-date by all parties involved as well as operating guidelines for field personnel.

1.3 The first such statement of this nature in this field was titled "Rehab 80". It was produced by the Forests Department, who co-ordinated input from a range of organisations and specialist workers.

1.4 Following a period of implementation and further research and analysis, previous prescriptions are to be withdrawn and replaced by this prescription.

Rehab 84 represents the best current "State of the Art" describing techniques to be used in bauxite mine rehabilitation in the western jarrah forest.

1.5 New techniques (i.e. departures from this prescription) may be introduced as research projects, so long as

- the location and timing is approved by the Forests Department, in co-ordination with the appropriate research working groups;
- accepted research procedures for experimental design, measurement and follow-up are fulfilled.

1.6 The prescription will be reviewed at 12-monthly intervals, at which time new strategies or techniques may be considered for incorporation.

Input for this review will be considered from the various authorities involved in the rehabilitation operation and the review will be co-ordinated by the Forests Department. Any changes to objectives, strategies or operational techniques will be subject to comment and acceptance by the appropriate government authorities, and mining company.

2. THE OBJECTIVE

An objective is a broad statement of what it is expected to be achieved within known constraints.

The overall objective for rehabilitation of bauxite mines in the western jarrah forest is:

"To regenerate a stable forest ecosystem, planned to enhance or maintain water, timber, recreation, conservation and/or other nominated forest values."

Specific goals (not listed in order of importance since priorities may vary with designated land use) are:

2.1 **Water values**: To ensure that mined areas provide acceptable water quality and quantity.

2.2 **Timber**: To grow a forest which has the potential for eventual sawlog production.

2.3 **Recreation**: To maintain existing recreational values where possible and to provide increased opportunities for forest-based recreational activities in accordance with Forests Department regional and divisional recreation plans.

2.4 **Protection**: To conserve the residual soils; to control dieback spread; and to ensure that unacceptable fire hazards do not accumulate.

2.5 **Landscape**: To create a rehabilitated landscape visually compatible with the adjoining remnants of indigenous forest.

2.6 **Conservation**: To re-create, in the long term, floral, faunal and soil characteristics compatible with the remnant indigenous forest.

In seeking to meet goals for rehabilitation of mined areas, it is important to remember that the desired end result is a multiple-use forest in which rehabilitated stands are fully integrated.

3. REHABILITATION STRATEGIES

3.1 To develop prescriptions for rehabilitation procedures for each mined area, in accordance with the designated land use priority and land use management plans.

3.2 To conduct research into means of improving rehabilitation procedures.

3.3 To monitor the regenerated areas for their capacity to sustain long-term production of the forest values listed in the objective.

3.4 To develop remedial treatments should monitoring reveal that rehabilitation objectives are not being achieved.

4. REHABILITATION PLANNING

Rehabilitation planning occurs at two levels:

The first is broadscale regional minesite planning on a 5-year time-scale. The second is the detailed operational annual planning on a pit-by-pit basis.

4.1 Broadscale regional planning

The mining company is required to produce each year an updated 5-year Mining and Management Plan for approval by Government. In the preparation of these plans, the following aspects of rehabilitation are to be considered:

- land use priorities;
- the sequence of mining and rehabilitation;
- access for mining and future management;
- location of mine facilities;
- dieback hygiene;
- landscape planning;
- water management systems and water course protection; and
- buffer zones for fire protection.

This prescription deals with Mining Operations only within Water production MPAs, as defined in Forests Department GWP 87 of 1982. At this stage no mining is proposed for other MPAs.

4.2 Special preliminary planning in recreation MPAs

Where mining is proposed in areas designated as Recreation MPAs, preliminary survey and site analysis is required. Part of this work is the responsibility of the mining company and part is that of the forest officer-in-charge. However, best results will occur if a team approach is used.

Responsibility of the company:

(i) Carry out an inventory of natural and cultural (i.e. man-made) landscape attractions and recreational features within the mining envelope. The purpose of the inventory is to identify those attractions or features such as water bodies, large rock outcrops, prominent view points, historical sites and existing recreation development which are considered important to the existing or potential recreational use of the area. Such attractions can be classified on the basis of various criteria such as uniqueness and opportunity for relocation elsewhere (in the case of man-made attractions).

(ii) **Record** vegetation types which will be cleared or threatened as a result of mining and identify special elements worthy of special protection. Information on vegetation will be used in selecting species mixes for scrub reseeding following mining.

Responsibility of the Forest Officer:

(i) Assess the mining envelope in terms of its existing and potential significance for recreation at a regional and local level. The assessment should identify the opportunities which exist for land and water-based recreation activities, taking into account both likely demand for such activities and the capability of the area to service those demands.

(ii) Through reference to regional and divisional land use management plans, determine the area's suitability for post-mining recreation development and use (the term 'suitability' refers to capability as modified by other land use requirements and constraints). Proposed recreation development is to be specified in terms of location, type and extent of facilities required.

(iii) Decide on post-mining access requirements for recreation development and use of the area and design the mine road network to fit these requirements wherever practicable.

(iv) Examine and modify proposed mining plans with respect to the location, extent and timing of operations to reduce the visual impact these operations will have on landscape values and recreational features as determined in the inventory stage. In this regard, attention should be paid to considerations such as the size and configuration of mining pods as they relate to the character of the surrounding landscape, timing and sequence of rehabilitation and treatment of adjacent stands.

4.3 Annual operational planning

Detailed proposals for each minepit are prepared 12 months in advance of rehabilitation. (Note: when better information on proposed dates of mining for specific areas becomes available, an 18 month lead time should be aimed at).

Each detailed proposal is prepared jointly by Forests Department (F.D.) and mine company staff, and is to deal with the following factors:

- pit identity — nominated by F.D.:
- dieback hygiene, drainage, erosion control and water management — specify measures to be adopted from initial drilling through to completed rehabilitation;
- management of "islands" of unmined forest;
- species to be used;
- any special features to be incorporated or retained (e.g. pit walls) as part of the rehabilitated landscape;
- access, and location of mining facilities/ structures;
- scheduling in sensitive area.

A conceptual rehabilitation proposal will be prepared for each area, and must be initialled as "Agreed To" by the local Forests Department officer-in-charge.

Contentious or unusual areas should be referred to the Mining Operations Group which recommends annual rehabilitation plans to the Conservator of Forests for approval. This group contains representatives of the Forests, Mines, Public Works and Agriculture Departments and the Metropolitan Water Authority.

Departures from the agreed conceptual plans are sometimes desirable. This should only happen after formal field consultation between Forests Department and company staff.

4.4 Special fire protection provision

When rehabilitation is scheduled within the boundaries of the Jarrahdale or Dwellingup Townsite Protection Plans, refer to these plans for details of tree and shrub species permitted and access required.

5. DIEBACK MANAGEMENT

Because bauxite mining and rehabilitation involves massive soil and vehicular movement under all weather conditions, together with substantial modification to natural drainage patterns in the forest, close attention to dieback hygiene is essential.

The two key management aims are:

(i) to minimise the spread of infection into dieback-free forests and minesites;

(ii) to manage access and drainage so as not to expand areas which favour the survival and pathogenicity of the pathogen.

Dieback hygiene measures are specified in detail in other prescriptions dealing with drilling, timber salvage, clearing and topsoil handling — i.e. operations not dealt with in this prescription.

Other dieback control requirements which are relevant to rehabilitation are dealt with in sequence as they arise.

6. PREPARATION OF PITS FOR PLANTING

When mining is completed, the earthworks required for the preparation of pits for planting requires the following operations:

- deep ripping on the contour to fracture the compacted pit floor;
- landscaping;
- replacement of overburden;
- shallow rip on the contour.

6.1 Ripping

Deep ripping is required to fracture the compacted pit floor so as to provide an "anchor" for the returned top soil by controlling the overland flow of water. Shallow ripping may be required to re-establish the control of overland flow if re-compaction occurs during landscaping.

In general

All compacted pit floors require ripping prior to landscaping. The distance between parallel rip lines is to be determined by the need to ensure a continuous fracture of the compacted subsoil. This will include areas covered by fill during landscaping.

The depth of ripping should not be less than 1.5 m. Ripping should be done using a winged tyne to maximise subsoil fracture.

Ripping should be done when the soil is dry (i.e. when subsoil moisture content is less than field capacity) so as to maximise subsoil breakup and minimise compaction.

6.2 Landscaping

Pit walls will be battered and smoothed. Occasional retention of pit walls may be prescribed, subject to the recreation plan and attention to the potential safety problems of perched boulders, and long-term stability of the cliff wall.

6.3 Overburden and top soil will then be evenly respread over all areas to be regenerated. The distribution of this material within pits will be in accordance with the following dieback hygiene requirements:

(i) No infected material to be carried to dieback-free areas.

(ii) Minimise the movement of overburden and top soil.

(iii) Clean plant and machinery before entry to dieback-free areas where required.

(iv) Move soils only in dry conditions.

All soil movement must be agreed to by the Forests Department.

6.4 When compaction occurs during landscaping and overburden replacement a second shallow ripping or scarifying process may be required on the contour to re-establish the control of overland flow of water.

In areas where public access is to be encouraged, the ground surface will be levelled by scarifying during and/or following the second ripping operation.

6.5 Throughout the pit preparation work, care must be taken not to import, or bring to the surface, large boulders, i.e. those whose size and density renders the future forest floor untrafficable. Use as a guideline — height not to exceed 30 cm and density less than 1 per 100 square metres. Special measures may be necessary to deal with this problem.

6.6 Islands or inliers of low grade ore sometimes occur within a pit. It is desirable that these areas remain undisturbed. However, there will be occasions approved by the Forest Officer when the islands are both cleared and stripped.

When this occurs the unmined caprock will be "popped" with explosives to provide planting sites and ameliorate run-off. Blasted craters will be graded level prior to respreading overburden and top soil.

7. WATER MANAGEMENT

7.1 Careful water management must be considered in every phase of the operation from initial clearing and road construction through to completion of rehabilitation.

7.2 A variety of water management systems may be adopted, depending on land use priority, site, and the nature of the particular catchment or storage facility involved.

7.3 Criteria for success

Irrespective of the system which is used, it must satisfy the following basic criteria:

- There must be minimum topsoil erosion within pits.
- There must be no long-term ponds of water lying either within or below pits or roads.
- The need for long-term maintenance must be minimal.
- The system must be acceptable in terms of costs, aesthetics and land use priority.
- On proclaimed catchments the system must meet standards of stream turbidity, chemical and biological purity prescribed by the appropriate water supply authority.
- Mined areas must not be the source of unacceptable peak flood levels as prescribed by the water authorities.
- Off proclaimed catchments streams draining the area influenced by mining must not increase unduly in turbidity or chemical pollution.

7.4 Water management systems

Pits can be designed/constructed so as to (i) retain and infiltrate water, (ii) discharge water or (iii) some combination of retention and discharge.

7.5 In catchments where water retention and infiltration is prescribed, this will be achieved by:

(i) Infiltration and silt trapping in the contoured rip lines and:

(ii) Collection of overland flow either in a series of midslope contour banks and a pit bottom sump or by a system of grade discharge banks directing overland flow to predetermined sump areas within the pit.

Each sump must have the capacity to cope with the runoff from a 10 day 15 year storm event as calculated from meteorological records and minepit characteristics. This design will be based on an accepted hydrological model with an appropriate safety factor of 2.

Where contour interceptor banks are constructed these should be established at up to 10 m vertical intervals. Such banks may not exceed one metre in height nor have steep sides which will present an obstacle to future access. Where specified, contour interception banks must be provided with suitably constructed overflows and non-erodible spillways. Construction of these devices must be completed before the first autumn rains.

Where grade discharge banks are used, these will discharge into stabilized waterways which direct the water to detention sumps at the base of the pit. Grades of grade banks will not exceed 1:100. Sump and drain locations will be indicated on the conceptual rehabilitation plans.

Note: It is recognized that the use of a water retention system may give rise to prolonged pools or saturated zones within or just below pits, and this does not conform with one of the success criteria for water management.

7.6 In catchments where the discharge of water is prescribed, water management will be achieved by:

(i) Infiltration and silt trapping in the contoured rip lines and;

(ii) Control of overland flow by grade banks and slow release detention ponds or filter systems.

Each slow release detention pond or filter system must have the capacity to handle the runoff from a 10 day 15 year storm event, as calculated from meteorological records and minepit characteristics. Stable overflow sections are to be provided so that more extreme runoff events will not cause severe erosion or damage.

This requires the installation of adequate grade banks not exceeding a grade of 1:100 approximately along each 10 m vertical contour within each pit, and the construction of a discharge system at the bottom of the pit. This discharge system must adequately filter the water and must be so constructed to avoid saturation or erosion of jarrah forest downslope of the pit.

7.7 Drainage from mine access roads, haul roads or from pits must not flow into unmined jarrah forest, but must be channelled (via ponds or filters) directly into water courses.

7.8 All erosion control earthworks must be completed before the first effective autumn rains (i.e. generally before 30th April each year). See Section 6.1.

Standards will be monitored and remedial action specified using an appropriate Inspection and Action Checklist.

8. PLANTING

8.1 Planting layout and design

8.1.1 As a general rule, tree species will be established as mixtures. Pure stands may be planted in localised portions of the landscape.

In every mixture, favour species indigenous to the Darling Range and with roughly similar growth rates. Species mixes will be determined in advance and specified in the rehabilitation plan by the Forests Department.

8.1.2 Plant spacing will be varied according to the detailed site rehabilitation objectives. In some areas such as at prominent view points or vistas and along selected areas of road, some areas may be left unplanted. In other instances, trees may be planted in small groups or clumps to minimise the rigid plantation effect created by row planting on a regular spacing.

8.1.3 Aim to achieve a stocking of about 600 planted trees/ha.

8.1.4 Do not plant trees on overflow channels.

8.1.5 Commence planting when the soil profile is thoroughly wet after about 10th June. Cease planting by 1st August.

8.1.6 Seedling specifications: plants in jiffy pots or paper pots, approximately 12 cm in height with a minimum of 2-4 pairs of leaves. Pots and soil mix sterile. Jiffy pots to be broken open and roots trimmed before planting.

8.2 Before planting commences, all pits will be re-examined by the Forests Department and those that are deemed by the Forest Department to be inadequately prepared, will not be planted, but carried over for improved preparation and planting the following year.

8.3 Access for planting crews must be preplanned and specified so as to minimise traffic through the unmined forest to minimise disease spread and across the prepared pit to minimise erosion.

8.4 The forest officer in charge of each area must ensure that a detailed record of species and provenances planted and treatments given is made at the completion of the job.

8.5 Selection of tree species for planting

Criteria for selection of tree species to be used are:

(i) tolerance to dieback;

(ii) fire resistance;

(iii) capacity for roots to penetrate the dense kaolin layer;

(iv) useful timber;

(v) proven longevity, and growth to maturity in the mine pit environment;

(vi) visual compatibility with indigenous forest;

(vii) useful nectar source.

There are currently no tree species with proven capacity to satisfy all these criteria. Pending continuing studies into a wide variety of species in pits and arboreta (and new arboreta establishment), the following species will be planted:

High in the original landscape (i.e. the original jarrah forest uplands, or relatively free-draining sites):

E. wandoo
E. laeliae
E. accedens
E. resinifera
E. maculata.

Low in the original landscape (i.e. water-gaining sites):

E. patens
E. saligna
E. calophylla

Swamps and pit sumps:

E. patens
E. megacarpa
E. rudis

Other species which may be included as minor components on pit banks and edges where there is a reasonable soil depth:

E. muellerana
E. diversicolor
E. microcorys

Jarrah (*E. marginata*) will be sown onto the upland sites at a rate of 0.25 kg pure seed per hectare. Blackbutt (*E. patens*) may be sown at a similar rate into the low-lying regions.

8.6 Seed sources

Seed provenances for all tree species are to be laid down by Forests Department. See 8.4 for recording.

8.7 Fertilizer

Apply 100 gms of Monoammonium phosphate per plant at about 3 weeks and again at about 9 weeks after planting.

Fertilizer to be placed within 15 cms of the base of the plant, in a spear hole or stamped depression.

8.8 Success criterion for planting/fertilizer operation

Eighty per cent survival of planted species at 9 months after planting, as determined by a 10% systematic sample of rows.

Areas of 0.5 ha and above which fail to meet this criterion, to be rescheduled for replanting the next winter.

9. UNDERSTOREY ESTABLISHMENT

9.1 The aim of understorey establishment is to assist with erosion control, soil building and general site rehabilitation. Species to be used will be reviewed for each site each year. Criteria for species selection will be dieback tolerance, appearance and nutritional value.

9.2 Base species to be used will be selected from: *Acacia pulchella, A. lateriticola, A. drummondii, A. extensa, A. myrtifolia, Kennedya coccinea* and *K. prostrata*. Where other species are included in the seed mix, Forests Department approval must be obtained.

9.3 Specific species should be added for particular sites — e.g. ti-tree and sedges for sumps and swamps, wildflowers such as hovea, kangaroo paws, Hardenbergia etc., for roadsides and recreation sites. (See Section 4.2) and other species endemic to the site if the rehabilitated pit is dieback-free.

Species of low flammability and height growth, or no understorey at all may be prescribed for special fire management zones.

9.4 Species not to be used are non-indigenous species, Proteaceae or large woody and inflammable species such as Albizzia.

9.5 Scrub seed mixes will be determined in advance and specified in the rehabilitation plan for each pit and for specific sites within pits.

9.6 Fertilizer: Areas to be seeded will be broadcast fertilized with 450 kg/ha of superphosphate before sowing.

9.7 Application Rate: Mixed seed will be sown at the rate of 1 kg/ha.

Seeding is to be done by ground application and must be completed by 1 June each year.

9.8 Success Criterion: 1 plant established per square metre, 9 months after sowing, as determined by stocked quadrat survey of each pit.

Areas of 0.5 ha or greater not stocked at this rate to be re-seeded the following autumn. Light scarification may be necessary to promote seed germination in areas re-seeded in year 2.

10. ROADS

10.1 The road network which remains after rehabilitation must conform to a predetermined plan.

10.2 This plan will be drawn up from approved 5 year mining plans, and will cater for:

(i) access for mining;
(ii) access for rehabilitation;
(iii) access for future forest management.

10.3 The basic planning principle is to aim for the minimum number of well surfaced, low topography roads, consistent with provision for public access and disease management and fire protection.

10.4 Unwanted roads will be rehabilitated by:

(i) recovery of gravel for re-use elsewhere;
(ii) ripping and erosion control;
(iii) seeding and planting in harmony with surrounding forest.

11. PRESCRIPTION REVIEW

Next date for review of this prescription: May 1984.

Glossary

arboretum : a place where trees from various localities are propagated and grown, as individuals or in small stands, for scientific or educational purposes.

bauxite : a form of laterite containing commercially exploitable levels of alumina.

biotic : all the natural living organisms and their life processes in a given area.

canopy : the cover of branches and foliage formed by tree crowns.

clone : a group of plants derived by asexual reproduction from a single parent.

colluvium : a heterogeneous mixture of loose incoherent rock fragments, scree and mud which has moved downslope under gravity.

conductance (leaf) : the capacity to transmit water vapour through leaf stomata.

detritus : fragments of disintegrated rock material that have been moved from their original site.

dieback : the progressive dying, from the top downward, of twigs, branches or tree crowns.

dieback disease : in Western Australia, particularly applied to the effects of the root rot fungus *Phytophthora cinnamomi*.

dieback disease intensification : the build-up of activity of *P. cinnamomi* at a site leading to decline and death of susceptible species.

dieback disease susceptibility : the ease and rapidity with which the pathogen *Phytophthora cinnamomi* is able to bring about the decline and death of a species.

dieback-free forest : forest apparently free of infection from the pathogen *P. cinnamomi*.

ecology : the study of living organisms in relation to their environment.

ecophysiology : the study of the physiological adaptation of an organism to its environment.

ecosystem : the interacting system of a biological community, both plant and animal, and its non-living surroundings.

endemism : the restriction of the distribution of an organism to a particular area.

evapotranspiration : the loss of moisture from the terrain by direct evaporation plus transpiration from vegetation.

exotic : introduced from another locality.

feral : an introduced or domestic animal now living in the wild, as in 'feral cat'.

incipient dieback disease : forest in which *Phytophthora cinnamomi* is present or suspected, but dieback symptoms are yet to appear.

infection : the presence of *Phytophthora cinnamomi*, or some other disease, in a particular locality as revealed either by positive identification of the fungus or development of characteristic disease symptoms.

infiltration : the passage of water through the surface of the soil, via pores or small openings, into the soil mass.

infiltration capacity : the maximum rate at which a given soil can absorb falling rain, when the soil is in a specified condition.

interception : the capture of raindrops by plant cover.

interfluve : the area of land between two rivers in the same drainage system.

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.

Management Priority Area (MPA) : an area of forest managed according to its dominant use under a Land Use Management Plan.

matrix flow : the movement of soil water through the soil matrix.

monadnock : a residual hill standing above the general level of a landscape.

mulch : organic material such as cut grass, straw foliage, sawdust, bark chips or woodchips used as a covering for the soil to conserve soil moisture and check weed growth.

overland flow : that part of streamflow originating from rain which fails to infiltrate the mineral soil surface at any point as it flows over the land surface to channels.

parent material : weathered rock material upon which soil-forming processes operate to create soil.

permeability : the ability of a soil or rock to transmit water.

percolation : the passage of water under hydrostatic pressure through the interices of a soil or rock, excluding the movement through large openings.

phanerozoic : applied to the time-span during which remains of plants and animals have accumulated abundantly within sediments.

phenology : the science which is concerned with the time of appearance of characteristic periodic events in nature, especially as those events are modified by environmental factors.

phytogeography (plant geography) : study of ranges of plants over the earth and of the causes, present and past, underlying their characteristic distributions.

piezometric surface : the level to which water rises in a well sunk into an aquifer.

podsol : a soil formed under cool, moist conditions with a vegetation of coniferous forest or heath, especially from sandy materials, resulting in intense leaching of bases, salts and iron and aluminium compounds.

porometer : a small portable instrument for measuring leaf conductance.

preferential flow : the movement of soil water in preferred pathways such as root channels rather than through the soil matrix.

provenance : the geographical source or place of origin of a given lot of seeds or plants. Within a species, provenances are likely to exhibit some genetic differences.

recharge : soil water which penetrates to a temporary or permanently saturated zone.

regeneration : the process of forest renewal, or the plants resulting from natural regeneration process.

saturated throughflow : lateral flow in the soil under saturated conditions.

sawlog : a log large enough to produce sawn products.

scarify : to break up the forest floor and topsoil preparatory to natural regeneration or direct seeding.

scleromorphy : plant form characterized by small rigid leaves, short internodes and small plant size, usually considered adaptations to aridity and infertility.

silviculture : the art and science of establishment and tending of forest.

stemflow : that portion of the gross rainfall which is caught on the vegetation canopy and reaches the litter or mineral soil by running down the stems or trunk.

stoma (pl. stomata) : pore in the epidermis of plants, present in large numbers, particularly in leaves, through which gaseous exchange takes place. Each stoma is surrounded by two 'guard-cells', whose movements, due to changes in turgidity, govern opening and closing of pore.

throughfall : that portion of gross rainfall which directly reaches the forest litter through spaces in the vegetative canopy and as drip from leaves, twigs and stems.

transpiration : the process by which water in plants is transferred to the atmosphere as water vapour.

turbidity : diffusion of light caused by sediment suspended in a fluid; provides one measure of water quality.

understorey : the lower stratum of a multi-storeyed high forest.

unsaturated zone : that part of the soil profile in which all the pore spaces are not occupied by water.

variable source area (contributing area) : the area of a catchment contributing to storm runoff.

water yield : the quantity of streamflow draining a catchment usually expressed as an annual average volume, or volume per unit area, or as a percentage of the annual average catchment rainfall.