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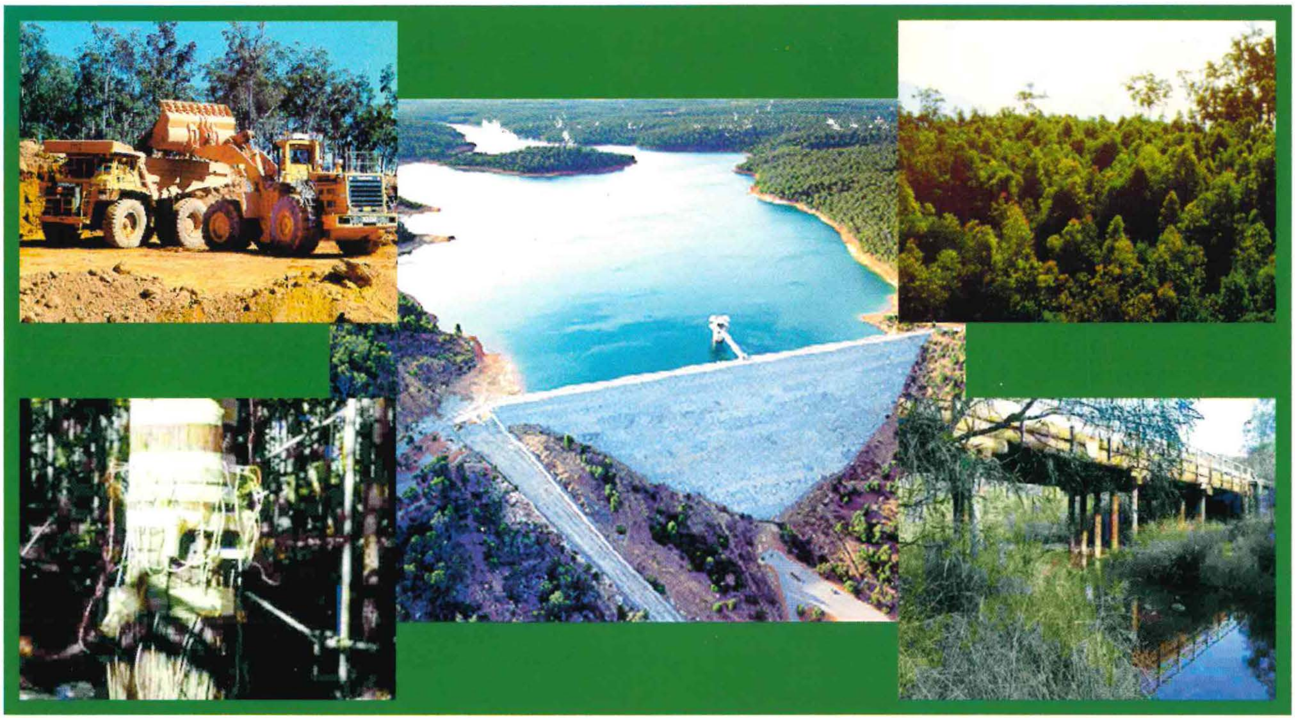
Hydrological and Associated Research Related to Bauxite Mining in the Darling Range of Western Australia—1997 Review



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1998

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Cover photographs:
The Wungong Reservoir for Perth water supply, with views of bauxite mining, rehabilitation of bauxite pits, a hydrological research project, and a river in the forest

HYDROLOGICAL AND ASSOCIATED RESEARCH RELATED TO BAUXITE MINING IN THE DARLING RANGE OF WESTERN AUSTRALIA - 1997 REVIEW

Report prepared by the Bauxite Sub-Committee of the Steering Committee for Research on Land Use and Water Supply

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Contents

Summary

The Darling Range, in the south-west of Western Australia, consists of an undulating plateau bounded to the west by an escarpment and merging to the east with a large peneplain that forms the wheat belt of Western Australia. The high rainfall of the Darling Range, combined with its forest cover andalumina rich laterite, have made it the focus for the land uses of potable water supply, forestry and bauxite mining. To ensure that the last two can be undertaken without compromising the first, there is an extensive research programme into the hydrology of the Darling Range. This report outlines the bauxite mining related hydrological and associated research that has been completed up to the end of 1997.

Two companies undertake bauxite mining within the Darling Range. Alcoa of Australia Limited is the largest with operations at three locations in the western, high rainfall zone of the forest. Worsley Alumina Ltd. operates a single mine in the Mount Saddleback region of the eastern, lower rainfall section of the Darling Range. This report focuses on the current and proposed future hydrological research activities associated with Alcoa, concentrating on studies relating to possible future mining in the intermediate rainfall zone (IRZ — 900 to 1 100 mm annual rainfall).

The area of Alcoa's mineral lease 1SA encompasses most of the developed metropolitan water supply catchments for Perth, the irrigation supply catchments in the Harvey River Basin, and the northern portion of the Collie River Basin. Alcoa's current operations are in the western, high rainfall zone (HRZ > 1 100 mm annual rainfall). An estimated 30% of Alcoa's bauxite reserves are located to the east of the HRZ, in the IRZ.

As part of the revised 1978 Environmental Review and Management Programme (ERMP), for the Wagerup Alumina Project, Alcoa committed 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 the water resources"*. The eastern, lower rainfall zone is normally taken as the IRZ which is considered a transition zone between the HRZ with its high rainfall and low salt storage and the LRZ (low rainfall zone < 900 mm annual rainfall) with its low rainfall, high salt storage.

The Technical Advisory Group (TAG), appointed by the Environmental Protection Authority (EPA) to review the ERMP, highlighted the need for joint planning of the mining operations between the State Government and the company and for broader based co-ordination of research programmes. As part of a broader process for rationalisation of research into land use and water resource related issues, including bauxite mining, a 'Steering Committee for Research on Land Use and Water Supply' (RSC), was established by the State Government. Programmes specifically related to bauxite mining were supervised by a 'Bauxite Sub-Committee' (BSC), chaired by the then Water Authority of Western Australia and more recently by the Water and Rivers Commission.

Research programme outline

It was established early in the deliberations of the BSC that resolution of the Alcoa commitment related to IRZ mining would be best addressed by a dual process of predicting the impacts of mining by computer simulation and confirming if necessary by an experimental mining operation within the IRZ. This became known as the 'Trial Mining' programme. The objective of the programme was to identify and instrument a 'typical' IRZ bauxite-containing catchment, to examine the salinity status and hydrological processes of the catchment, to develop a computer model capable of simulating the impact of mining and rehabilitation on the catchment. Then, if the simulated impacts on water resources were within an acceptable range, to undertake the mining and rehabilitation of the catchment as a demonstration and confirmation exercise.

What was unofficially termed the 'Trial Mining' programme was redefined in detail in 1990 and, as a co-operative programme between the then Water Authority of WA and Alcoa of Australia Ltd, was identified as the 'Joint Intermediate Rainfall Zone Research Programme' (JIRZRP). The programme was further developed by the BSC into the form outlined by Croton and Dalton (1994a). This programme was submitted to, and endorsed by, the RSC in 1994. A central feature of the programme is the development of computer models that simulate the effects of bauxite mining at the small and large catchment scales. Development of hydrological models capable of reflecting the complex hydrological processes, and specifically the water and salt discharge mechanisms of the Darling Range, has proven technically demanding and time consuming. Models used to date include simple parametric and stochastic models, semi-distributed models such as LASCAM (Sivapalan and Viney, 1994a) and fully distributed models such as TOPOG (O'Loughlin, 1986; Vertessy *et al.*, 1996) and WEC-C (Croton, 1997).

Paralleling the model development work has been research on, and collection of, detailed information on the hydrological processes of the Darling Range. This has included:

1. Studies of soil salt and groundwater salinity distributions across the Darling Range
2. Instrumentation of experimental and demonstration catchments in the HRZ and IRZ
3. Studies of plant water relations both in undisturbed jarrah forest and in rehabilitated mine pits
4. Soil water dynamics studies on forest and minepit soil profiles
5. Collection of other base data such as Leaf Area Index (LAI), by field and remote sensing techniques, of forest and mine area revegetation.

The present demonstration-mining programme for the IRZ is based on the medium scale Jayrup catchment (45.6 km^2), located north-east of Dwellingup. It contains the experimental mining catchments of Cameron West and Central as sub-catchments, is itself a sub-catchment of the Big Brook catchment and discharges to the Serpentine Reservoir.

Results and discussion

The recent development of a functional, fully distributed model (WEC-C) and the accumulation of sufficient data sets to facilitate application of the model to a realistic mining scenario, are significant advances towards realising the ultimate objective regarding future bauxite mining in the IRZ. In particular, the estimates for likely effects of mining in the Jayrup catchment on the stream inflow salinities of the Serpentine Reservoir have changed considerably due to these advances. The 1994 estimate of the peak increase in inflow salinity to Serpentine reservoir from mining in the Jayrup catchment under average rainfall conditions was 18 mg/L. The 1997 predictions using WEC-C for a similar mine plan and rainfall regime was 1.8 to 2.4 mg/L. An increase of this magnitude is not considered to be detectable by a normal sampling programme given that the average salinity of the reservoir was estimated to be 195 mg/L.

In December 1997 these results were presented to the Executive of the Water and Rivers Commission. They have in turn referred them to the Mine Management Programme Liaison Group (MMPLG) as an acceptable hydrological basis for MMPLG approval of Alcoa's 1998 mine plan submission to mine the Jayrup catchment.

Implications for management

It is significant that the simulations undertaken to date have used Alcoa's existing and well established HRZ mine development, mine planning and rehabilitation techniques and operations. The results indicate that for limited scale operations in the IRZ, as simulated, no changes to existing practice are merited. It will be an essential component of the JIRZRP to undertake simulations of future operational scale IRZ mining and rehabilitation scenarios. Should such simulations indicate unacceptable adverse impacts, alternative management strategies will need to be developed.

Future research

The JIRZRP, as presently defined, envisages the need for continuation of the programme until at least 2020. Clearly it is now a vital component to undertake the experimental and demonstration mining exercise and to collect post mining and rehabilitation data for comparison with model simulation results.

The WEC-C model is believed capable of further refinement and improvement. This to some extent will be based on the quality and range of input data. Review of existing data sets and their quality will continue to be essential. The WEC-C model will be applied to other Darling Range catchments to improve model calibration and confidence in the mining predictions.

Large scale catchment models, such as LASCAM, will be further developed. A large catchment, parametric version of WEC-C is proposed; the present practical limit for WEC-C on a PC type computer is about $100km^2$, though this should rise to about $500km^2$ by the year 2000. An important component of future modelling will be the development of close links between models, their input data, and systems for review of modelling results. It is hoped to completely integrate the models and the GISs that handle their data.

Estimation of vegetation Leaf Area Index (LAI) by LANDSAT imagery has become a central component of data preparation for modelling. Present relationships between spectral data and LAI for the various vegetation types are still very preliminary. A significant challenge will be to refine these relationships and to improve the understanding of vegetation water use efficiency, the relationship between LAI and actual plant water use, for various vegetation types including swamp zone vegetation and mine revegetation.

1. Introduction

The Darling Range in the south-west of Western Australia consists of an undulating plateau bounded to the west by an escarpment and merging to the east with a large peneplain that forms the wheat belt of Western Australia. The high rainfall of the Darling Range, combined with its forest cover and alumina rich laterite, have made it the focus for the land uses of potable water supply, forestry and bauxite mining. To ensure that forestry and bauxite mining can be undertaken without compromising potable water supply there is an extensive research programme into the hydrology of the Darling Range and the water balance of its forest ecosystem. This report outlines the bauxite mining related hydrological and associated research that has been completed up to the end of 1997.

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The area of Alcoa's mineral lease 1SA encompasses most of the developed metropolitan water supply catchments for Perth, the irrigation supply catchments in the Harvey River Basin, and the northern portion of the Collie River Basin. Alcoa's current operations are in the western, high rainfall zone (HRZ > 1 100 mm annual rainfall). An estimated 30% of Alcoa's bauxite reserves are located to the east of the HRZ in the IRZ.

As part of the revised 1978 Environmental Review and Management Programme (ERMP), for the Wagerup Alumina Project, Alcoa committed 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 the water resources"*. The eastern, lower rainfall zone is normally taken as the IRZ which is considered a transition zone between the HRZ with its high rainfall and low salt storage and the LRZ (low rainfall zone < 900 mm annual rainfall) with its low rainfall, high salt storage.

The Technical Advisory Group (TAG), appointed by the Environmental Protection Authority (EPA) to review the ERMP, highlighted the need for joint planning of the mining operations between the State Government and the company and for broader based co-ordination of research programmes. This led to the appointment in June 1979, by the Hunt Steering Committee, of a working group to consider bauxite mine research, with particular emphasis on research for the IRZ. As part of a broader process for rationalisation of research into land use and water resource related issues, including bauxite mining, a 'Steering Committee for Research on Land Use and Water Supply' (RSC), was established by the State Government. Programmes specifically related to bauxite mining were supervised by a 'Bauxite Sub Committee' (BSC), chaired by the then Water Authority and more recently by the Water and Rivers Commission. The present BSC has members from: Water and Rivers Commission (W&RC), Department of Conservation and Land Management (CALM), CSIRO, Curtin University and University of Western Australia; as well as industry representation by Alcoa of Aust. Ltd. and Worsley Alumina Ltd.

Croton (1990) reviewed all bauxite hydrological research and defined a programme which was renamed 'Joint Intermediate Rainfall Zone Research Programme' (JIRZRP). Croton and Dalton (1994a) refined Croton's earlier programme and set a detailed work programme for the period up to 2020; this was submitted to, and endorsed by, the RSC in 1994.

The following report briefly summarises key aspects of the hydrological and associated research, particularly as it relates to IRZ research, and provides extensive reference lists of related studies and research. In many instances the references quoted will direct the reader to further relevant studies that are considered too numerous for itemisation here. The reference list includes HRZ studies not quoted in the text, but which have some relevance.

2. The Darling Range - description, hydrology and land uses

2.1 The Darling Range

In order to assess the effects of mining and rehabilitation it is necessary to have an understanding of the natural environment. This chapter summarises the topography, geology, soils, climate and hydrology of the principal bauxitic area and the research that has been undertaken on the natural system. A large percentage of this research has not been undertaken as a direct part of the JIRZRP but is nonetheless essential background for the JIRZRP. Also included in this section are short discussions of the land uses of the Darling Range and a reference to jarrah dieback disease.

2.1.1 Topography of the Darling Range

The Darling Range forms the western boundary of a large peneplain extending hundreds of kilometres inland. The western edge of the Darling Range is formed by an escarpment 250 to 300 m in height (see Figure 1). Close to the Scarp the drainage is more incised with deep V-shaped valleys, due to the higher rainfall and resultant streamflow, and the local relief is often greater than 100 m (Bettenay *et al.*, 1980). Moving inland the valleys become broad and U-shaped.

2.1.2 Geology and geomorphology

The principal bauxitic area encompasses the western region of the central section of the Darling Range (see Figure 1). The Darling Plateau was developed on the Archaean crystalline rocks of the Yilgarn block. The rocks are principally granites and granitic gneisses, and these coarse-grained felsic rocks have intruded older, generally mafic rocks now represented by several metamorphic belts, such as the Saddleback group. The granites themselves have been intruded by dolerite dykes that often follow the major north-westerly structural trend of the region. Being more resistant to weathering than the granitic country rock, dolerite dykes underlie many of the ridges and catchment divides; soil profiles over dolerite are also generally shallower than over granite. The Darling Range is extensively mantled with deep lateritic profiles formed on all rock types.

Permanent groundwater occurs in the soil profile and within fractures in the basement rock, but fractures are rare and the base of the aquifer system is usually assumed to be the top of the basement rock (Martin, 1989). In the valley floors groundwater may discharge to streams with this being more likely in the western, higher rainfall portions of the Darling Range (Schofield *et al.*, 1989).

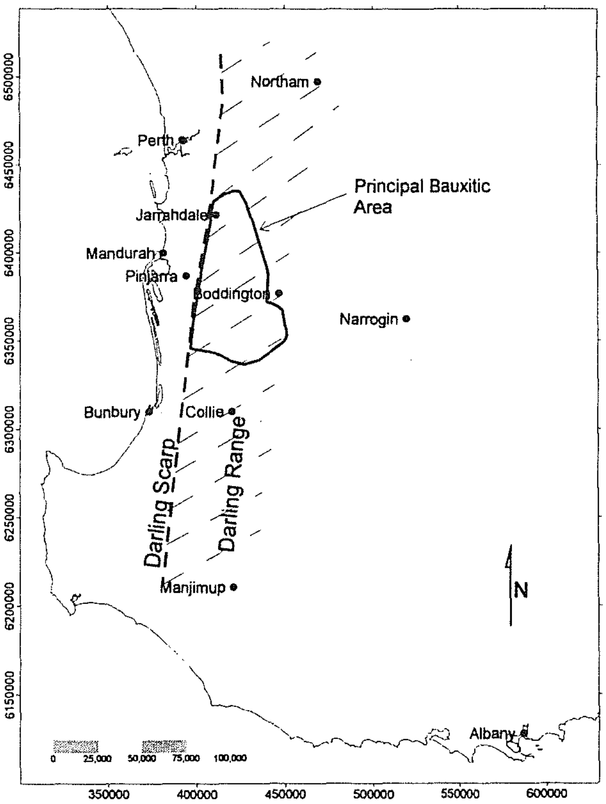

Figure 1: Locality plan showing the Darling Scarp, the Darling Range and the principal bauxitic area.

2.1.3 Soils

Churchward and McArthur (1980) synthesised previous studies of the northern jarrah forest into a regional soil and landform map that recognised three primary geomorphic units and nine soil associations. The three primary geomorphic associations were Lateritic Uplands, Shallow Valleys and Deeper Valleys. The Lateritic Uplands unit comprised the Cooke, Dwellingup, Yalanbee, Goonaping and Wilga soil associations.

For the lateritic uplands a descriptive soil classification system of six morphological zones is used: superficial deposits, duricrust, mottled zone, pallid zone, weathering zone, and basement rock. There is often a friable zone between the duricrust and mottled zone, not generally discussed in the soil science literature; but important because it often contains economically recoverable alumina, in which case the term bauxite is used. In his discussion of a typical Darling Range soil profile McCrea (1987) includes bauxite as a subset of the mottled zone soils. In many cases the morphological zones can be found to follow sequentially with distinct boundaries down a soil profile, though they sometimes grade into one another or alternate with depth.

The shallow valley soil associations comprised the Murray, Helena and Yarragil. The shallow valleys typically consist of yellowish-brown sandy gravels on gentle slopes (Yarragil) and yellowish-brown sandy gravels and gravely yellow duplex soils on moderate slopes. The Deeper Valley soil associations were the Murray and Helena, which consist of red and yellow earths on moderate to steep slopes of deeply to very deeply incised valleys.

2.1.4 Climate

The climate of the Darling Range is described as Mediterranean, with dry hot summers and wet, cool winters from May to September. There is a strong gradient in annual rainfall that decreases from west to east. Average annual rainfall ranges from over 1 300 mm/yr near the Darling Scarp to 450 mm/yr in the eastern Avon valley. Approximately 80% of the annual rainfall is initiated by cold fronts migrating off the Southern Ocean during the winter months. Rainfall intensities are generally low; 90% of all rainfall in the western portion of the Wellington Dam catchment is received at less than 25 mm/hr (Williamson *et al.*, 1987).

Summer rainfall is usually caused by sub-tropical thunderstorms producing rainfalls of 50 to 70 mm in several hours. Tropical cyclones occasionally reach the Darling Range from the north-west bringing extremely high intensity rainfall, though there may be many years between individual events.

Potential evaporation, as measured by evaporation from a Class A evaporation pan, exhibits a strong south-west to north-east gradient (Williamson *et al.*, 1987; Luke *et al.*, 1988). For much of the Darling Range, rainfall only exceeds pan evaporation for four or five months of the year, and annual evaporation exceeds rainfall by increasing amounts from the south-west to the north-east.

Maximum summer air temperatures are very high; the mean daily maximum temperature for February at Dwellingup is 29.5°C. Winter minimum temperatures are considered moderate; the minimum temperature recorded in the Darling Range is -4.5°C at Wandering.

2.1.5 Vegetation

The dry sclerophyll native forest of the Darling Range is dominated by *Eucalyptus* species, some of which are unique to the area, among them jarrah (*E. marginata*) and marri (*E. calophylla*). Other tree species found in the jarrah forest include yarri (*E. patens*) and bullich (*E. megacarpa*). The dominant trees typically reach heights in excess of 30 m although due to much of the forest having been logged in the last 100 years few tall individuals remain. There is generally a middle storey of sub-dominant trees and shrubs (*Banksia*, *Allocasuarina* and *Persoonia* species) below the forest canopy and a ground cover of herbaceous plants below this (*Macrozamia*, *Hibbertia* and *Styphelia* species).

There is generally a strong correlation of vegetation with either soil type or landscape position. There is also a gradient in forest density from west to east in response to rainfall. Bettenay *et al.* (1980) found that the average basal area of the dominant trees ranges from 20 to 30 m^2/ha in the western portion of the Wellington catchment compared with 19 to 24 m^2/ha in the east. In the east, the forest often thins appreciably on the valley floors which tend to be broader and flatter; jarrah and marri are usually replaced by sparse wandoo (*E. wandoo*) or flooded gum (*E. rudis*). In the west, jarrah and marri often extend almost to the incised stream lines except where there are flat, swampy areas covered in dense stands of *Agonis* and other shrub species.

The roots of the dominant trees branch laterally, exploiting the surface soils; large sinker roots then extend vertically through the holes in the duricrust to exploit the sub-soils (Kimber, 1974; Dell *et al.*, 1983; Ruprecht and Schofield, 1990). Below the duricrust tree roots are concentrated in the vertical macropores that extend through the mottled and pallid zones (Johnston *et al.*, 1983). Live tree roots have been found at depths in excess of 35 m though root densities are very low beyond about 10 m (Dell *et al.*, 1983). There is often an increase in the density of fine roots just above the groundwater if the depth is not prohibitive (Kimber, 1974).

2.2 Darling Range hydrology and salinity

Due to its forest cover, the water balance of the Darling Range is dominated by evapo-transpiration, and streamflow, as a fraction of rainfall, is low. Trends in rainfall from west to east are well reflected in stream yields. Rainfall trends also control soil and groundwater salinisation processes.

2.2.1 Water balance

Evapo-transpiration

Evapo-transpiration is the major component of the water balance of the jarrah forest. Being a forest environment, primary components are: interception by canopy and stems, transpiration by upper, middle and under storeys, and leaf litter and soil evaporation.

Interception has been measured at 13.4% annual rainfall for a HRZ site and 9.8% for a LRZ site (Williamson *et al.* 1987). Croton and Norton (1998 - in press) assessed the components of interception at the Del Park catchment in the HRZ; canopy interception was 12 to 19%, stemflow was 3% and interception by the under-storey and litter layer was 7% of rainfall.

The annual evaporation from the understorey of a jarrah forest site near Dwellingup was estimated by Greenwood *et al.* (1985) to account for about half of the annual rainfall. This study used the ventilated chamber method that measured evaporation from soil, litter, ground flora and *Banksia grandis* trees. Greenwood *et al.* (1985) concluded that reduced evaporation caused by removal of trees during clearing and thinning operations could be counteracted by increased evaporation from this understorey layer.

Transpiration has been measured by heat pulse techniques for a number of species in the jarrah forest. Marshall (1993) estimated the water use of mature jarrah forest to be about 700 mm/yr. Marshall's findings contrasted with those of Greenwood *et al.* (1985) in that he found the dominant trees took up most of the water.

The total evapo-transpiration of the jarrah forest, when water stress of the vegetation is not a significant limit to transpiration, appears to be about 1 000 mm/yr (Marshall pers. com.).

Soil water dynamics and storage

Unsaturated soil water dynamics play an important role in the hydrology of the jarrah forest. Firstly, the deeply weathered lateritic profiles (average about 25m in depth) provide a large soil water store (Sharma *et al.* 1987; Ruprecht and Schofield, 1990) which leads to low water yields (Schofield *et al.* 1989) and sluggish streamflow hydrographs (Loh 1974). Secondly, vertical fluxing occurs as both matrix and preferred pathway flows, leading to a complex pattern, both spatially and temporally, of groundwater recharge.

Bari (1995) undertook a review of soil water dynamics studies in the Del Park catchment. He found that annual variation in unsaturated soil water storage was of order 275 to 550 mm, with the annual variation being greatest in the lower slope areas.

Deep groundwater

Groundwater recharge in the jarrah forest typically can occur via two mechanisms (Johnston 1987). The first mechanism is by matrix flow; the second is via preferred pathways, injecting water at depth into the soil matrix. Long term averages of groundwater recharge range from approximately 10% of annual rainfall in the HRZ to less than 1% in the LRZ (Ruprecht *et al.* 1990).

In higher rainfall areas, extensive permanent groundwater systems are typically found in the freshly weathered parent material above bedrock and in the lower section of the pallid clay horizon. The groundwater often discharges to the stream channel, even in first order catchments. Streamflow is rarely perennial, as evapo-transpiration by vegetation flanking the streamlines is usually larger than groundwater discharge. Local geological characteristics, such as dolerite dykes, may influence groundwater to discharge, prolonging stream baseflows through summer.

In lower rainfall areas groundwater does not normally discharge to streams and may be 15 m or more below the stream invert at the catchment outlet (Schofield *et al.* 1988). This results in streams ceasing to flow at least six weeks before similar streams in higher rainfall areas. In intermediate rainfall areas there is a transition between high and low rainfall areas; depending on local conditions, groundwater may or may not contribute to streams.

Although groundwater does not contribute significant amounts of water to stream yield, it has an important role in providing the mechanism for generation of saturated source areas (Ruprecht and Schofield 1989) and the discharge of saline groundwater leads to stream salinisation. Permanent clearing of forest vegetation has led to increased groundwater levels; salt stored in the unsaturated soil profile is thus mobilised and transported to the soil surface and streams. Stream salinisation due to permanent clearing of native forest has led to only 48% of divertable surface water resources in the south-west of Western Australia remaining fresh (< 500 mg L^{-1} TSS).

Streamflow

Infiltration excess overland flow is considered to be rare in the native jarrah forest; jarrah forest soils have high infiltration capacities that are rarely exceeded by rainfall intensities. Average surface soil hydraulic conductivities for native forest soils range from 10 - 21 m d^{-1} (Ruprecht and Schofield 1993; Sharma *et al.* 1987). However, a land use change, such as from forest to pasture, can induce a reduction in K_s by an order of magnitude (Sharma *et al.* 1987).

Although saturation excess overland flow is not considered highly significant with respect to water yield in the jarrah forest, instantaneous flood peaks are clearly dominated by the intensity of short-term rainfall on a small saturated source area of a catchment.

Shallow throughflow in the upper gravely sand horizon is considered to be the major source of streamflow in the jarrah forest. Stokes and Loh (1982) calculated that over 90% of streamflow for Salmon catchment originated from shallow throughflow.

Stream yields in the Darling Range are strongly correlated with rainfall: the average streamflow volume for catchments in the HRZ is of order 20% of rainfall, decreasing to 3% for the IRZ and to 0.5% for the LRZ (Croton, 1990).

2.2.2 Salinity processes

Soil salt storages

The major source of the salt that is stored in the soils of south-west Western Australia is sea salt carried inland with rain and dust (Wood, 1924). Salt precipitation is most prevalent in the south-west corner of the State near the coast, decreasing inland and to the north. Rainfall salinities are typically of the order 10-20 mg/L and result in salt falls of around 10-25 g/m^2. The salt is concentrated in the soil by plant water extraction and direct evaporation from the soil. The mechanisms of water and salt movement that lead to salt accumulation in the regolith were studied by Johnston (1988)

Reviews of salt storage data by Stokes *et al.* (1980), Johnston (1981), Slessar *et al.* (1983) and Tsykin and Slessar (1985) all verified early observations that soil salinity is relatively low in the high rainfall zone but increases rapidly with decreasing annual average rainfall. Tsykin and Slessar's data for 327 boreholes confirmed that in the Darling Range there is a low soil salt content zone extending east from the Darling Scarp to the 1 100 mm/yr rainfall isohyet; the average soil salt content for this zone was 4 kg/m^2. Salt content was found to increase in a near-exponential manner with distance inland and had reached 20 kg/m^2 by the 750-1 100 mm/yr rainfall zone. Croton (1991b) found that there were also north-south trends in soil salt storages in that section of the IRZ covered by the principal bauxitic area, with the lowest storages being in the north.

Groundwater salinities

Croton (1991c) studied groundwater salinities in the principal bauxitic area of the Darling Range. He found that in the northern section of the principal bauxitic area, groundwater salinities were essentially the same in the HRZ and IRZ, 438 mg/L and 447 mg/L respectively, while in the southern section of the principal bauxitic area they were very different, 191 mg/L and 837 mg/L respectively.

Discharge of salt to streams

In the Darling Range salt can discharge to streams in three ways: by direct runoff, throughflow discharge and groundwater discharge. Direct runoff is when salt fall is washed into the stream system by rainfall without having been stored in the soil. Throughflow discharge of salt is when the lateral flow of water within the soil and above an impeding layer leaches salt from the soil and carries it into the stream; this water is within a perched aquifer and is not part of the main groundwater system. Groundwater discharge is when the water of the permanent groundwater system discharges directly or indirectly into the stream, carrying the salt with it.

For forested catchments, groundwater discharge usually occurs only in the HRZ and the groundwater in the HRZ is reasonably fresh. For forested catchments in the IRZ and LRZ, where the groundwater is progressively more saline, the groundwater table does not normally intersect the soil surface even in the stream zone. The net result is that stream salinities for forested catchments in the IRZ and LRZ are relatively low as the salinities for direct runoff and throughflow are usually low.

Throughflow salinities can be relatively high when the groundwater system is able to discharge into the throughflow aquifer system; either by pressure generated from confinement of the deeper aquifer, or by capillary suction driven by soil surface evaporation and plant transpiration. In the latter case the salt tends to accumulate in the throughflow aquifer system during the dry summer months and is flushed into the stream system by winter throughflow. Williamson *et al.* (1987) calculated that 82% of salt discharged from Wights catchment seven years after clearing was via throughflow. Since the salt load being discharged was in excess of the pre-clearing salt storage of the layer in which throughflow was occurring, it was concluded that salt from lower in the soil profile was being discharged via the throughflow aquifer.

2.3 Land uses and dieback disease

The northern jarrah forest is subject to a number of land uses that include silviculture for water and timber production, mining and rehabilitation and conservation and recreation. Some of the land use practices have conflicts of interest which are compounded by the presence of dieback disease (*Phytophthora cinnamomi*), a dormant salinity risk and a strongly fire-prone environment (Havel, 1989).

2.3.1 Logging and burning

The northern jarrah forest has been subjected to logging for about 100 years, during which nearly all the forest has been cut over at least once. Logging practice and intensity have varied greatly according to the location, forest quality, and silvicultural practice of the day. As a result, the northern jarrah forest now consists of a mosaic of various mixed-age and even-age regeneration.

The Forest Management Information System (FMIS), developed by the Department of Conservation and Land Management (CALM), documents the areas available for forest management operations. The areas available within the HRZ and IRZ vary in size from one water supply catchment to another; in the six major water supply catchments, Mundaring, Canning, Wungong, Serpentine and Dandalups, areas suitable for silvicultural treatment range from 7% to 66%.

Recurrent fire is an integral part of the northern jarrah forest; the jarrah forest ecosystem is adapted to fire (Hingston *et al.*, 1989). CALM regularly undertakes controlled understorey fuel reduction burning to reduce the risk of wide-spread bush fire.

2.3.2 Mining and rehabilitation

Bauxite mining is a major land use within the northern jarrah forest. The principal mineralised region of Alcoa's Mineral Lease 1SA encompasses 50 to 60% of the northern jarrah forest and covers most of the developed metropolitan water supply catchments for Perth, the irrigation water supply catchments in the Harvey River Basin and a portion of the Collie River Basin. Of this mineralised region only a small percentage represents commercially viable bauxite deposits, estimated to represent approximately 4.5% of the northern jarrah forest. Since mining began in 1963, approximately 9000 ha of jarrah forest have been cleared for mining; the present clearing rate is about 500 ha per year (Croton and Bari, 1997). After the removal of bauxite, the pit is rehabilitated in consultation with CALM; procedures are designed to meet the end land uses specified by CALM, such as water supply, timber production, conservation or recreation. Around 7000 ha of the mined area had been rehabilitated by the end of 1996.

2.3.3 Dieback disease

Jarrah dieback is a disease caused by a fungus known as *Phytophthora cinnamomi* whose presence is demonstrated by the deaths of trees and shrubs and the resultant thinning of tree canopies. Davison and Shearer (1989) estimated the area of dieback affected state forest to be 180,000 ha or 14.2% of the forest. Dieback disease is favoured by the presence of warm and moist soil conditions and there is a concentration of the disease in the lowland areas in the jarrah forest where high soil moisture levels persist in the warmer summer months.

The disease may also have a major impact on forested areas higher in the landscape should poor vertical drainage combine with lateral throughflow to favour long distance, downslope dispersal of fungal propagules. Kinal (1986) compared the development of perched water tables and shallow throughflow, to the severity of disease caused by *Phytophthora cinnamomi* along a hillslope at Dawn Creek in the northern jarrah forest. He found that perching developed on the sandy clays immediately underlying the lateritic duricrust, and was more rapid, more extensive and more sustained in the high impact area than in the intermediate impact area. Perching also developed on the duricrust on the upper slope in the high impact area and occurred more rapidly than in areas further downslope. Perching of water high in the landscape increases the chance of inoculum dispersal over long distances downslope by cumulative throughflow events.

The variation in perching was related to properties of the soil profile. In the high impact area the duricrust was more continuous with fewer cracks and vertical channels, was thicker and closer to the surface, and the clay more finely textured.

Zoospores were recovered from water flowing through the coarse-textured soil overlying the duricrust, in winter and early spring, when the soil at depth was warmer than near-surface soil (Kinal *et al,* 1993). This indicates that soil temperatures favoured zoospore production, release and survival and that the year-round presence of zoospores in the soil was conditional only on rainfall.

2.4 Water resources

As about 70% of the Perth's reticulated water supply is from the catchments of the Darling Range, their correct management is a high priority with State Government. To provide an informed basis a comprehensive research programme is underway. The following is a brief summary of those components relevant to bauxite mining.

2.4.1 Water resources research

The effects of land use changes on the quality of water resources in the south-west of Western Australia has been researched for more than 20 years. Results show that in the HRZ the risk of increase in stream salinity following logging and revegetation is minimal. For example, there was no significant increase in stream salinity following silvicultural treatment at Conjurunup catchments (Robinson *et al.,* 1997). Similar results were also observed at the southern forest of Western Australia (Steering Committee for Research on Land Use and Water Supply (RSC), 1987a). In the IRZ the risk of transient increase in stream salinity is higher; stream salinity may double following clearing and regeneration (RSC, 1987a). In the LRZ the effect of logging and revegetation can be transient and result in a small temporary increase in stream salinity. For example, stream salinity at Yerraminnup catchments increased in the order of 20 mg/L TSS, and remained below 500 mg/L TSS following logging and regeneration (Bari and Boyd, 1993). However, if a catchment in the LRZ is cleared and not rehabilitated for a long time, stream salinity will increase more than ten fold before achieving a new stability (Ritson *et al.*, 1995; Mould and Bari, 1995).

2.4.2 Research on forest thinning to increase stream yields

The Steering Committee for Research on Land Use and Water Supply (1987b) and Stoneman and Schofield (1989) reported on the likely effects thinning of the jarrah forest would have on catchment yield. The Steering Committee estimated that yield increases between 11% and 18% of rainfall would be likely in the HRZ, with increases of around 11% of rainfall in the IRZ. They also reported strong inverse relationships between canopy cover and streamflow for catchments within the HRZ and the IRZ.

Stoneman and Schofield (1989) reported on a forest thinning trial undertaken on Yarragil 4L catchment in 1983. Yarragil 4L is 25 km ESE of Dwellingup and has an average rainfall of 1120 mm/yr, so it is on the divide between the HRZ and the IRZ. Only three years of post-treatment data was analysed by Stoneman and Schofield. They found that the groundwater level at a midslope position was rising at a rate of 1m/yr, which is similar to that observed elsewhere in the south-west. Before treatment, the watertable was 3 to 8 m below the surface in the streamzone, so this rate of rise would have to continue for some years before the groundwater would intersect the surface. Increases in streamflow were modest with a maximum annual increase equal to 31 mm of rainfall.

Robinson *et al.* (1997) studied the impact of forest thinning on three small catchments in the HRZ. They estimated peak increases in streamflow of 10 to 20% of rainfall and increases in two-year Average Recurrence Interval (ARI) flood flows by three to five times. They found no evidence of changes in stream salinities.

3. Bauxite mining and rehabilitation

3.1 Introduction

Mining is a transient land use but one which nevertheless transforms the character of the land surface for the period in which it is undertaken. This transformation affects all attributes of the land including the hydrology of the catchments in which the operations occur. Apart from the effects of actual ore extraction there are those associated with infrastructure such as haul roads, conveyors and crushers. In all cases vegetation is removed and the hydrology, most obviously surface runoff, is altered. Having areas cleared for mine development open for the shortest possible time, coupled with effective rehabilitation of mine pits and infrastructure, can significantly mitigate the adverse hydrological effects of mining. Alcoa's rehabilitation research and development programme in the Darling Range has progressed to a high level of sophistication and has included extensive hydrological investigation.

3.2 Rehabilitation planning and operations

3.2.1 Mine planning

As a result of the 1978 Revised Environmental Review and Management Programme for the Wagerup Alumina Project, responsibility for supervision of all mining and related operations in the Darling Range was given to the Mining and Management Plan Liaison Group (MMPLG), chaired by the Department of Resources Development (DRD).

A rolling five year mine plan proposal is submitted by Alcoa to the MMPLG annually, defining ore bodies proposed for mining and providing details of associated infrastructure development. At approximately five yearly intervals a strategic review is undertaken, detailing future mining direction within a twenty five year time frame. Following approval of each five year plan submission, Alcoa provides notice to CALM of the intention to access specific ore bodies for commercial removal of all forest timber produce from each defined area. After completion of timber harvesting and salvage operations the area is cleared of all remaining vegetation including stumps and crowns.

3.2.2 Mining and rehabilitation process

Bauxite mining in the Darling Range is a surface operation where alumina-rich ore pods of between two and 40 ha in area are mined by a truck and loader operation. Minable ore can be found anywhere in the landscape, except within the streamzones, and is usually considered economic if the depth exceeds two metres and alumina content exceeds 27.5%. The maximum depth of a minepit can exceed 10 m, though most mining occurs over the depth range three to four metres. The ore typically consists of the duricrust plus the friable layer composing the upper portion of the mottled zone. The extraction process normally consists of the following steps.

1. All millable timber and minor forest produce is removed. Any remaining vegetation is cleared and burnt.
2. The surface soil and gravel layers above the duricrust, average thickness 400 mm, are removed by scraper and either stockpiled or immediately spread on another mine area which is being rehabilitated. The top 50 mm of the profile is handled separately to preserve its seed store and quality as a growth medium.
3. The exposed duricrust is drilled and blasted or, more recently, ripped with a large crawler tractor.
4. Front-end loaders and back-hoe excavators place the ore into haul trucks that transport it to a central crusher.

From the time of clearing, various drainage measures are employed to minimise surface runoff: blasting of the duricrust at the downslope boundary of mine areas, construction of earth embankments, excavation of sumps for water collection, and ripping of mined-out areas to promote infiltration.

Once the area has been mined, the following steps are taken to rehabilitate the area. A more detailed account of the rehabilitation process has been provided by Baker, *et al.* (1995).

1. All pit faces are battered down using bulldozers and any areas of heavily trafficked pit floor are ripped to relieve compaction.
2. The pit topography is smoothed into the surrounding landscape and a holding sump, designed to contain a storm event with a recurrence interval of once in 20 years (Croton and Tierney, 1985), is formed at the downslope edge of the pit.
3. The surface soil and gravel layers are returned in two steps. This is to ensure that the top 50 mm of the forest soil remains on the surface.
4. The area is tilled using a "winged" tyne to a depth of up to 1.4m (Croton, 1985) to promote surface water storage and infiltration, and plant root penetration of the subsoils.
5. Seeding is undertaken immediately following ripping, using a comprehensive, provenance-correct seed mix of under-storey and over-storey plants.
6. Diammonium phosphate fertiliser is aerially applied once, towards the end of the first winter following seeding.

With regard to the areal extent of mining, about 9 000 ha have been cleared since mining commenced. The present clearing rate is about 500 ha per year. The distribution of bauxite within the Darling Range is far from uniform and while mining will only be conducted on a few percent of the whole Darling Range the percentage cleared in a given stream catchment can be much higher. The typical range for present operations in the High Rainfall Zone (HRZ) is 20 to 60% with the average being about 35%.

3.2.3 Rehabilitation objectives

The objective of the landscaping part of the rehabilitation process is to restore the topography to a form which will not preclude the implementation of future forest management activities, and in such a way as to minimise any loss of visual amenity which may have existed before mining. Once the landform has been restored, the area is revegetated in keeping with the designated land use of the area. Since the mid 1980's this had been defined as the restoration of a forest ecosystem visually compatible with the adjacent native forest and capable of sustaining the designated land uses of water and timber production, conservation enhancement and forest recreation. Recently this objective has been redefined to be "to restore a self-sustaining jarrah forest ecosystem, planned to enhance or maintain water, timber, recreation and conservation values".

3.3 Mine management and rehabilitation research

Since 1991 research into the rehabilitation of Alcoa's bauxite mining areas has been undertaken in three main areas: Botanical Diversity, Rehabilitation Productivity and Sustainability, and Fauna Studies. These programmes are described in detail in the triennial reports to the State Government, as required by the State Agreement Acts (Alcoa 1994 and 1997). These reports, covering the period 1991-1996, are summarised below.

3.3.1 Botanical diversity

Alcoa carries out a continuous programme of research, implementation and monitoring to try to increase the number of local native forest species that successfully establish in rehabilitated areas. In 1996 rehabilitation Alcoa achieved its objective of establishing at least 80% of the native plant species richness of jarrah forest control plots. This objective has been increased to 100% for year 2000 rehabilitation. Research to achieve this objective can be divided into two main areas: increasing the diversity of plants establishing from the returned topsoil, and increasing the diversity of plants seeded or planted in new rehabilitated areas. Increasingly this research has been directed towards the more difficult species, referred to as recalcitrant species. These are plant species that are common in the jarrah forest but are uncommon or absent in rehabilitated mine pits. This may be because they produce very little seed, or their seed is not viable, or if viable does not germinate readily. Tissue culture methods of propagation, or other vegetative means such as cuttings have been examined at length, and seed biology has been intensively investigated. Species investigated have been from the plant families Epacridaceae, Cyperaceae, Dillenaceae, Restionaceae, and Orchidaceae. This has been in collaboration with Kings Park and Botanic Gardens and Curtin University on projects funded through the Minerals and Energy Research Institute of WA (MERIWA). A number of new protocols have been developed for initiating species into tissue culture from seed embryos.

Planting trials have been undertaken to examine the various options available for the establishment of recalcitrant species. In 1996, 25,000 recalcitrant plants were grown by cuttings and tissue culture and planted at Alcoa's three mines.

A project was initiated in 1994 between Alcoa and Kings Park to develop the use of combustion products (smoke) to promote the germination of recalcitrant species. Treating rehabilitation pit soils with smoked water increased total germinates by 56% and species numbers by 33%. As a result of these studies, all broadcast seeds for use in mine rehabilitation by Alcoa are now smoke-treated.

3.3.2 Seed ecology

Since 1991 the development of procedures to re-establish the full suite of jarrah forest species in rehabilitated areas has been a key research focus area. An integral part has been the development of specific mixes of applied seed for each mine to supplement the natural soil seed-store.

Between 1994 and 1996 further detailed studies of germinable seed stores in jarrah forest sites have identified strong and significant seasonal variation. To maximise opportunities for the contribution of the soil seed-store to mine rehabilitation, additional guidelines and recommendations have been developed regarding optimum timing for rehabilitation operations such as topsoil stripping and seedbed preparation. These studies reinforced the practice of directly returning topsoil rather than stockpiling, and identified summer as the optimum time for carrying out all topsoil handling operations.

3.3.3 Rehabilitation productivity and sustainability

A 'jarrah trial' was set up in 1988 to study in detail the growth of jarrah and understorey plants on rehabilitated bauxite mines. Ward and Koch (1995) have reported in detail the progress of the trial.

Details of further rehabilitation research studies including fire (Grant *et al.*, 1997 four references), nutrient research (Ward and Koch, 1996) and soil microbiology have been reported by Alcoa in the Triennial Reviews.

3.3.4 Fauna

Nichols (1996) summarised the past 15 years of Alcoa's fauna research. Below is a summary of the fauna monitoring undertaken to date.

A GIS based system was developed in 1994 to store important fauna records. All historic data on rare or uncommon mammal, bird and reptile species were included.

Detailed fauna surveys are conducted in proposed future mining areas. Habitats important for the conservation of faunal diversity are identified, and recommendations presented for minimising the effects of mining operations on species and their habitats.

With regard to recent findings, the number of fox sightings has decreased following the fox baiting project Operation Foxglove. Similarly, no dingoes (which would also be susceptible to fox baits) have been sighted since Operation Foxglove commenced. The densities of feral mice in rehabilitation have decreased dramatically; the reasons are not fully understood, but the phenomenon is also known to occur as vegetation communities mature, e.g. following sand mining and fire. Densities of several mammal species appear to have increased since 1992. These include the chuditch, brush-tailed phascogale and two dunnart species, as well as the southern brown bandicoot and the western brush wallaby. Populations of all these would be expected to increase following the decline in fox numbers due to Operation Foxglove. There was no evidence of any mammal species declining due to the proximity of mining.

Valuable information has been obtained from the nest box project which, to date, has resulted in over 300 nest boxes being set up in rehabilitated mined areas and adjacent unmined forest. Eighty-eight percent of nest boxes in rehabilitation have already been used by one or more mammal species at some time. The mardo, pygmy-possum, chocolate wattled bat and the brush-tailed phascogale are among the most notable species to have been recorded. The project has provided important information on species distribution and biology.

The first 13 years of a continuing study on rehabilitated mine pit ant recolonisation has been reported by Majer and Nichols (1998). This study provides information related to the longer term performance of mine rehabilitation; it will be complemented by a study, initiated in 1997, of the response of spiders in areas of forest and rehabilitation subjected to burning (Brennan, 1997).

3.4 Dieback management and research

The aims of Alcoa's dieback research programme are to:

1. Improve the understanding of those aspects of the disease relevant to Alcoa and from this contribute to the design of mining and rehabilitation prescriptions.
2. Quantify the effects of mining on the health and diversity of the forest (including the rehabilitated areas).

In the period 1994 to 1996 collaborative research projects were undertaken with the following organisations:

1. CALM (Dr. G. Stoneman, Dr. B. Shearer, Ms. F. Bunny, Mr. M. Stukely, Mr. S. Carstairs).
2. Murdoch University (Dr. G. Hardy, Assoc. Prof. J. McComb, Assoc. Prof. B. Dell, Dr G. Roos).
3. Edith Cowan University (Dr. I. Bennett).
4. CSIRO (Dr. I. Tommerup, Dr. R. Hobbs, Dr. M. Byrne).

Details of dieback research, including aspects of disease management in forest and rehabilitated bauxite mined areas, have been reported by Alcoa (1994 and 1997).

4. Hydrological research

4.1 Background of the JIRZRP

In 1994 Alcoa and the Water Authority of W.A. submitted a proposed Joint Intermediate Rainfall Zone Research Programme (JIRZRP) to the W.A. Government's Steering Committee for Research on Land Use and Water Supply (RSC). This programme presented the details of joint research between Alcoa, Water Authority of W.A. (WAWA), CSIRO, and the Centre for Water Research based at the University of W.A. The programme components, direction and timetable were accepted by the RSC subject to continued overview by that Committee's Bauxite Sub-Committee (BSC).

The JIRZRP was developed to formalise existing and proposed research associated with bauxite mining, that addressed the issue of the potential for an increase in stream salinity as a result of mining activities in the Intermediate Rainfall Zone (IRZ) (900-1 100 mm/yr average rainfall) of the northern jarrah forest.

There are two objectives of the JIRZRP. The first is *"to determine what impact bauxite mining in the intermediate rainfall zone will have on the water resources of the region"*. This objective was developed from a commitment made in 1978 by Alcoa in the Environmental Review and Management Programme (ERMP) for the Wagerup Alumina Project. The second is *"to document the forest, mine and rehabilitation management practices which should be used in the intermediate rainfall zone"*. This objective was set so that when mining operations enter the IRZ they can be effectively managed. To meet these objectives a programme structure based on eight study areas has been defined. This is shown in Figure 2.

Figure 2 shows a progression from base data collection and analysis on the left-hand side; to modelling in the centre; through to estimates of likely impact, and development of management procedures, on the right-hand side. The JIRZRP was also divided geographically into northern and southern IRZ components due to observed differences in soil and groundwater salinities. Experimental data collection for the southern IRZ is centred on the Cameron catchment group, planned for experimental mining in the period 2005 to 2011. In the northern IRZ, a demonstration and confirmatory mining exercise was planned for the Cobiac catchment between 1998 and 2000. However, the intended closure of the Jarrahdale mine at the end of 1998 has resulted in a suspension of further northern IRZ research.

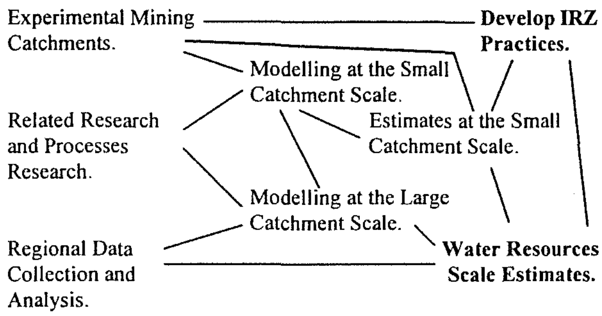

Figure 2: JIRZRP structure.

The modelling components of the study are based on the development of a distributed small catchment model, which allows the accurate simulation of groundwater flow, inter-flow and streamflow responses to mining; and a large scale catchment model which can integrate these small scale effects into estimates at the water resources scale. Regional data collection programmes provide the necessary background data with which these estimates can be compared. Of importance to the programme is the development of "key" parameter data sets that allow a workable definition of the region's geomorphology and its relation to hydrology and to stream salinity risk.

Alcoa has continued to retain the full time services of Water and Environmental Consultants (WEC), specifically for the development of computer modelling capability and generally to oversee the technical and hydrological aspects of the programme. The timetable of the JIRZRP, agreed by the RSC and reported in the 1991/93 Triennial Report, remains fundamentally as reported at that time. Consideration of the implications of premature closure of the Jarrahdale mine, and consequent supply of bauxite to the Kwinana refinery from the Huntly mine, brings the commencement date for the Jayrup experimental operation forward to the last quarter of 2003. The basis of the JIRZRP remains unchanged. That is, to allow a government decision to be made in sufficient time so that, if mining is to be permitted, mining operations can gain general IRZ access by about the year 2020, at latest 2022. The timing of the experimental mining component of the programme is critical in order to allow sufficient post rehabilitation hydrological monitoring and the analysis of its results.

In the period 1994 to 1996 the hydrological modelling component of the programme has undergone significant revision. The development of the TOPOG model for Darling Range catchments under an AWRAC partnership research programme between CSIRO Division of Water Resources, the then WA Water Authority (WAWA), and Alcoa, was concluded in 1995. The TOPOG model was found to be limited in its ability to simulate the effects of bauxite mining in the Darling Range, and the time and manpower predicted necessary for improving its suitability were beyond that deemed acceptable by the partnership.

The large scale catchment model LASCAM, developed by the UWA Centre for Water Research, has proved valuable for predicting the impact of changes in land use on catchment yield, but requires more development if it is to be used with confidence to simulate the effects on stream salinity of bauxite mining in the IRZ.

Toward the conclusion of the TOPOG project, WEC commenced the development of a fully distributed catchment model. The model, named 'WEC-C' (Water and Environmental Consultants — Catchment), has now reached an advanced stage of development. It will be used as the principal tool for simulating the stream flow and salinity effects of mining in the IRZ. Independent assessment of the conceptual basis, the numerics and the validity of the assumptions used in the WEC-C model has being undertaken, with the endorsement of the BSC, by Prof. D.A. Barry formerly of the Centre for Water Research at the University of WA and now at the University of Edinburgh (Barry 1997a and 1997b).

In 1995, following endorsement by the BSC, approval was given by the RSC for Alcoa to undertake experimental mining in the Cameron West and Central catchments, representing an estimated 10Mt bauxite. Simulation using a parametric model (Croton and Dalton, 1994b) indicated that the likely impact of mining on the quality of water in the Serpentine Reservoir was within natural variation (in the order of 5-6 mg/L increase in TSS in the reservoir in a period of average rainfall).

Approval is being sought by Alcoa to include the proposal to mine the Cameron Corridor in the 1998 submission of mine plans to the Mining and Management Programme Liaison Group (MMPLG). This includes endorsement by the RSC and their advice to the MMPLG that demonstration mining of the Jayrup catchment is consistent with research requirements necessary for Alcoa to meet the 1978 ERMP commitment.

4.2 Catchment studies

A significant finding of the JIRZRP in 1991 was that the soil and groundwater salinity characteristics in the IRZ north of the Serpentine River (Northern IRZ) differed markedly from those of the IRZ south of the Serpentine River (Southern IRZ) (Croton, 1991a and Croton, 1991b). It is not clear why, but the two areas were therefore treated separately for research purposes. This was significant when accessing the Balmoral region of the Serpentine catchment as part of the strategic mining programme for the Jarrahdale mine; at that time the JIRZRP was designed to accommodate experimental mining operations in the Cobiac catchment (Northern IRZ) and in the Cameron catchments (Southern IRZ) (see Figure 3). The Gordon catchment was identified and instrumented as a control catchment and for climatological monitoring of the Southern IRZ. It has recently been determined, with Alcoa's announcement at the end of 1996 of the closure of the Jarrahdale mine by the end of 1998, that the investigations associated with mining in the Balmoral region of the IRZ, including experimental mining of the Cobiac catchment, will become redundant.

Proposals for mining in the Cameron region have also been revised. Experimental mining of the two small catchments (Cameron West and Central) in isolation represents only a limited example of probable mining operations in the IRZ generally. This, together with what were regarded as conservative model predictions to date, necessitated the JIRZRP revision. Alcoa sought endorsement by the RSC that, after refinement of the WEC-C model and subject to an acceptable simulated mining impact on water quality, the experimental mining would be expanded to represent a more substantial scale of operation. This would include the ore bodies in the part of the IRZ that would, in a realistic mine planning scenario, be accessed en route to the Cameron West and Central catchments; the total area is termed the 'Cameron Corridor' and is contained within the fully instrumented, medium-scale Jayrup catchment. The quantity of bauxite in the Cameron Corridor is estimated at 35-45 Mt and, if approval is given, will be mined over a period of approximately 10 years from 2003.

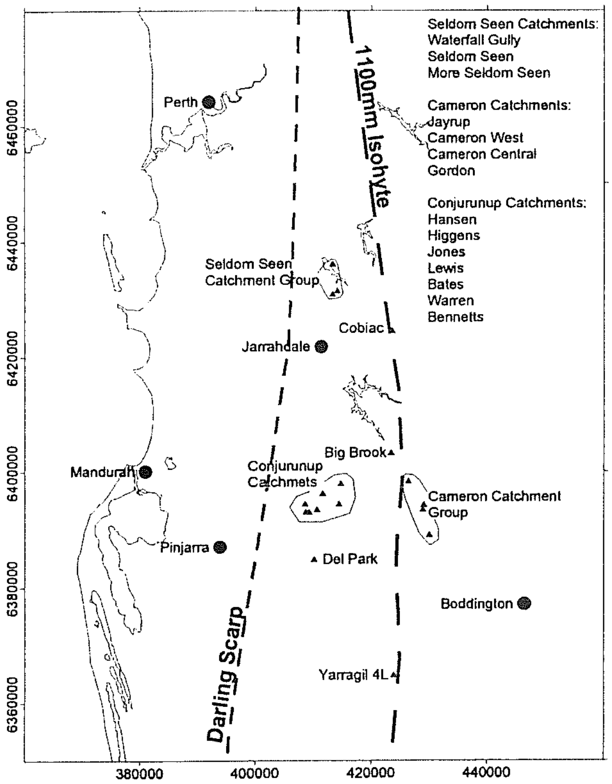

Figure 3: Location of gauging stations for JIRZRP catchments.

In 1997, following extensive review of its capability, the WEC-C model was used for mining simulations of the Cameron West and Central and Jayrup catchments. A number of rainfall scenarios were modelled including low, average and high rainfall cases. The results were published by Croton *et al.* (1997 and 1998); there was also a number of supporting reports reviewed by the BSC. The simulations predict a maximum increase in reservoir inflow salinity of 7.6 mg/L and an increase in reservoir storage salinity of 4.3 mg/L., for the high rainfall scenario using 1942-1996 rainfall data.

Not all studies undertaken as part of the catchment studies component of the JIRZRP are in the reference section of this review; some additional studies have been informally reported and have therefore not been included in the reference list. These should be consolidated with other relevant information and formally reported in 1999.

The JIRZRP time frame for the southern IRZ, approved and endorsed by the RSC in 1995, is shown in Table 1 below. It is anticipated that a revised version of this programme will be prepared and published in 1998, after it has been approved by the RSC.

4.3 Regional data

Over the last 20 years Alcoa has collected soil salinity and groundwater level data across the Darling Range from approximately 2 500 boreholes, drilled using either hollow auger, air core or vacuum drilling methods. The hollow auger method allows the collection of undisturbed soil samples and soil cores, determination of bedrock depth and type, identification of aquifer zones, and installation of piezometers that permit collection of groundwater level and groundwater quality data. The air core method is much faster and more economical but samples collected are disturbed and not continuous and only small diameter piezometers can be installed. The vacuum drilling method allows the collection of only disturbed soil samples, from above the water table, but is the fastest and most economical method. Piezometers are not normally installed in vacuum drilled boreholes.

All the borehole and soils data are stored on Alcoa's ROT database which includes data from; 37 000 soil samples, 12 500 groundwater salinity samples and 70 000 groundwater level observations. Alcoa have a continuing groundwater level and groundwater quality monitoring program to collect data related to forest management and bauxite mining activities. This programme is periodically reviewed and changed to meet the needs of the JIRZRP and is currently focused on the Del Park, Lewis, Cameron West, Cameron Central and Gordon experimental catchments and the Jayrup demonstration catchment.

Table 1: Southern IRZ programme (Huntly Mine). (NB. The table below shows the existing programme that was approved by the RSC).

Year	Activity
1993 (Q4)	Prepare operational plan, including logging, clearing, mining and rehabilitation for Lewis catchment in HRZ.
1994 (Q4)	Complete instrumentation and borehole establishment in Cameron group of catchments including establishment of Jayrup gauging station.
1994 (Q2)	Likely commencement of 60m ore development drilling in Camerons.
1994 (Q4)	Provide Alcoa's Mine Development Group with recommendations on the need for trial mining of Cameron catchments, plus the scale of proposed mining, based on clearing needing to commence in Q4 2004.
1995 (Q1)	Comprehensive review of southern IRZ regional database.
1995 (Q1)	Review predictive modelling capacity for southern IRZ and carry out preliminary estimate of stream salinity hazard.
1996 (Q3)	Commence MFP extraction from Lewis catchment.
1995/6	Log two Cameron catchments (single summer operation).
1997 (Q1)	Commence mining in Lewis catchment.
1997 (Q2)	Review Cameron ore quality and possible impacts on ore extraction rate.
1997	Review all relevant data and predictive modelling capability to make final decision to commence mining in Camerons in 2005. Obtain endorsement of Cameron mining proposal from RSC. Include Camerons in 5 year mine plan submission to MMPLG. Undertake modelling prediction of the potential impact of mining the Cameron Corridor (Jayrup catchment) to support proposal to RSC to allow demonstration mining.
1998	Include Cameron Corridor in Huntly mine plan submission
2000 (Q2)	Complete rehabilitation in Lewis catchment.
2003	Commence clearing in Cameron Corridor
2005 (Q1)	Commence clearing in Cameron catchments.
2010	Review all post rehab. monitoring data from Lewis catchment and determine need for further data acquisition or for programme conclusion.
2011	Complete Cameron rehabilitation.
2015	Review all monitoring data and re-run computer models. Verify/adjust model predictions
2017	Include general IRZ entry into 5 year plan submission to MMPLG together with qualified endorsement of RSC. (Based on proposed 2022 IRZ entry).

With regard to analysis of the data, Tsykin and Slessar (1985) related the collected soil salt data to climate and geomorphological variables. Their analysis included regressions of soil salt storage profiles by five metre layers. Tsykin and Croton (1988) described the relationships between soil salt storage and landscape position for a data set of 543 boreholes and found that soil salt storages were greatest at the streamzone. Croton (1991b) and Croton (1991c) studied the relationship of soil salt storage, groundwater salinity and groundwater levels to geomorphological attributes. Croton (1991a) assessed the geomorphological attributes of first and second order catchments in the IRZ and developed a system for assessing catchment typicality.

4.4 Early predictive modelling

For the duration of the 'Trial Mining' project, the need for an acceptable predictive computer model has been seen to be of key importance. Whilst a number of different models were used to make earlier predictions, they were not considered capable of reflecting the complexities of water and salt discharge mechanisms, the alteration of the soil profile, the distribution of mining within the catchment, and the strong influence of climate and vegetation changes well enough to provide a basis for approval of experimental mining. The models used in the early studies are reviewed briefly below.

4.4.1 Peck model 1

Using a simple parametric model, Peck (1976) predicted that bauxite mining and rehabilitation in the More Seldom Seen catchment of the HRZ would increase stream salinity by 7 mg/l TSS. The subsequently observed salinities were 20 mg/L higher than before mining (Davies *et al.*, 1995).

4.4.2 Peck model 2

A more detailed model (Peck *et al.*, 1977) was developed to predict the effect of mining on the inflow stream salinity to South Dandalup Dam. This model accounted for the spatial, temporal and transient nature of bauxite mining. The major conclusions from the predictions based on this model were:

1. Bauxite mining alone (without dieback) will have negligible effect on South Dandalup Dam stream salinities.
2. In conjunction with dieback, significant increases in stream salinity are possible. However substantial control could be achieved by reforestation.

4.4.3 Schofield-Peck model

Schofield (1988) presented a catchment mass-balance model for predicting stream salinity increases following agricultural clearing and mining, based on the Peck Model 1 (Peck, 1976). The model was validated on Wights catchment and applied regionally to the high, intermediate and low rainfall zones. The predicted stream salinity increases for mining and for mining and dieback (with no reforestation) is shown in Table 2.

Table 2: Predicted average stream salinity increases for different rainfall zones (Schofield, 1988).

	Salinity increase (mg/L) TSS		
	HRZ	IRZ	LRZ
Peck-Model 1			
Mining	11	34	266
Mining + Dieback	18	66	1 128
Schofield-Peck Model			
Mining	17	60	378
Mining + Dieback	23	90	1 210

Both the Peck-Model 1 and Schofield-Peck models are steady state models and do not take into account the transient nature of the disturbance.

4.4.4 Model by Croton (1990)

Croton (1990) reviewed the limitations of the above three models and developed a dynamic form of Schofield's model. He also modified the model so that it represents a catchment within the IRZ, rather than the region as a whole. He used the results from Ruprecht *et al.* (1990) with an average clearing area for mining of 35% to produce an estimated mining related increase in stream salinity of 111 mg/L for a fully mined catchment within the IRZ.

With ore distribution maps and estimated requirements for bauxite, Croton made an estimate of the effect that mining the IRZ section of the South Dandalup River water supply catchment would have on reservoir inflow salinities. The expected increase in reservoir inflow salinity was 11 mg/L. This increase in salinity would be for a period of around 10 to 15 years, with 10 year periods of increase and reduction at each end.

This figure of 11 mg/L must be seen as a probable overestimate as it assumes that groundwater discharges will occur for a period of 10 years for each mine area. In the IRZ the watertable is usually metres below the soil surface in forested catchments and has to rise this distance before groundwater can discharge. A salinity increase of 11 mg/L would also be difficult to detect among the year to year fluctuations in stream salinity resulting from natural climate variability.

4.5 Other Darling Range models

A number of other models have been applied to the study of stream flows and stream salinities of the Darling Range. These include the following.

4.5.1 Darling Range Catchment Model

The Darling Range Catchment Model (DRCM) was developed by the Water Authority of W.A. in the early 1980s. It has been described by Hopkins (1984) and Mauger (1986). The model can be categorised as a distributed lump model in which the catchment is discretised into sub-catchments and sub-areas, each of which has its hydrology described by a series of parametric equations. Many of the 20 parameters in the DRCM were based on published or implied relations and have physical significance. Considerable attention was given to estimation of Leaf Area Index (LAI) and its use in estimating interception and transpiration. Other physical processes such as channel routing and solute transport were considered by the model. The DRCM has been applied to 11 small catchments in the northern and southern jarrah forest and the medium sized catchments of Conjurunup Creek and Jane Brook. The fit appeared good, though hydrograph matching of actual gauged flows to model outputs was used to calibrate the parameter values.

The DRCM was considered to be cumbersome in terms of input requirements and output generation. Because of computing capability at the time, it had to be run on a mainframe computer overnight in batch mode. Also, expertise in the development and operation of the model were lost as staff moved on to other duties. For these, rather than hydrologic reasons, its use has ceased. It has been replaced by the LASCAM model.

4.5.2 CWR model

The CWR water and chloride model was developed for the simulation of small experimental catchments in south-west Western Australia. The chloride model is described by Sivapalan and Jeevaraj (1991). The water balance model was an extension of an earlier version described by Ruprecht (1992). The water balance model includes components for interception, evaporation, quick response streamflow, sub-surface flow, groundwater flow and water balances in shallow, deep and stream-zone water stores; the chloride balance model assumes advection only and that diffusion and dispersion fluxes are negligible. The CWR model was a forerunner of the LASCAM model.

4.5.3 LASCAM

LASCAM (Large Scale Catchment Model) is a development of the Centre for Water Research — University of W.A. It is a quasi-lumped model in which the catchment studied is divided into a number of sub-catchments and a multi-store parametric model is developed for each. In the Darling Range it has been applied to: the Conjurunup catchments, assessment of the impacts of mining in the Serpentine Reservoir catchment, and numerous other small catchments.

4.5.4 TOPOG

TOPOG has its genesis in the WETZONE program described by O'Loughlin (1986). Since then it has been developed into a fully distributed, deterministic catchment model that employs operator splitting to simulate vertical fluxes via the Richards Equation, lateral fluxes at depth using a finite element groundwater model and near surface lateral fluxes using a flow tube technique. Some details of its formulation are given by Beverly (1992). Papers describing its application to catchments outside Western Australia include Vertessy, *et al.* (1993, 1994 and 1996). The present version of TOPOG has not been applied to Darling Range catchments. TOPOG has a web site at www.clw.csiro.au/topog.

4.6 Modelling using WEC-C

The WEC-C model has now been, or is being, applied to a number catchments in the south-west of W.A. Past studies directly relevant to the JIRZRP are listed below.

4.6.1 Del Park study

Croton (1995) applied the WEC-C fully distributed catchment model to the study of the hydrologic effects of bauxite mining on the Del Park catchment. The intention was to test the model's utility for catchment water yield studies in the Darling Range, with particular emphasis on assessing the effects of land use changes such as bauxite mining or forest thinning. Croton found that the model appeared to perform well with no significant problems being encountered during the simulations. In particular, the split operator within WEC-C appeared suitable and the computational speed was high in comparison with most other distributed models.

With regard to the results of the simulations, the groundwater system beneath the mine areas was predicted to have a peak rise due to mining of between two and four metres, and to have returned to about one metre above unmined levels by six years after revegetation. This was consistent with reported findings (Ruprecht *et al.*, 1990). The streamflow increase due to mining was estimated to peak at 21 mm/yr, and to have declined to 7.4 mm/yr by eight years after revegetation of the mine areas. These increases in streamflow were less than those reported for other catclunents (Loh, *et* *al.*, 1984). This variation was probably due to differences in mine practices at Del Park.

Croton recommended that the model be further developed and applied to catchments within the Darling Range, and that solute transport be incorporated in the model so that it could be applied to studies of stream salinity as well as stream yield. This has been done and descriptions of the numerics and application to Darling Range catchments are given by Croton (1997) and Croton *et al.* (1997).

4.6.2 Cameron mining study

Croton *et al.* (1997) undertook a study to define the likely changes in stream inflow salinities for the Serpentine Reservoir, as a basis for gaining approval to undertake experimental and demonstration bauxite mining in the Cameron area. The study was based on the WEC-C model simulating catchment responses in terms of streamflow and stream salinity. The catchments modelled for both unmined and mined scenarios were the medium scale catchment of Jayrup and the small catchments of Cameron West and Central that are nested within Jayrup. Two rainfall and evaporation series were used as model inputs, an average case of 42 years in length and an actual case of 55 years in length based on the period 1942 to 1996. The results from the modelling simulations were up-scaled to the Serpentine Reservoir with information from Bari and Mauger (1997) and with direct calculation using a Serpentine Reservoir stream inflow series provided by J. Ruprecht of the W&RC.

Croton *et al.* (1997) predicted increases in stream inflow salinities to the Serpentine Reservoir due to bauxite mining in the Cameron area to be significantly less than those previously estimated. Using a parametric model, Croton and Dalton (1994b) estimated that for the average rainfall and streamflow case the peak increase in inflow salinities would be 18 mg/L if the main ore bodies within the Jayrup catchment were mined. For a similar mine plan, Croton *et al.* (1997) estimated the average case salinity increase would be 1.8 to 2.4mg/L, or one seventh to one tenth of the original estimate. Increases of 1.8 to 2.4 mg/L would not be detectable by a normal sampling program given that Bari and Mauger estimated the average salinity for Serpentine Reservoir at 195 mg/L. These increases of 1.8 to 2.4 mg/L were less than that predicted by Croton and Dalton (1994b) for mining of Cameron West alone, 3.6 mg/L, or for mining both Cameron West and Central, 6.5 mg/L.

Croton *et al.* (1998) was an addendum to Croton *et al.* (1997) which outlined the results for two extra cases: simulations of the whole Jayrup catchment for a high rainfall case, data from the period 1942 to 1994; and a low rainfall case, data for the period 1975 to 1996.

The primary conclusion of the addendum was that the estimates made in the main report, of the high rainfall case peak salinity differences for the Serpentine Reservoir were conservative. The original estimate of peak inflow salinity difference between the mined and unmined states for the high rainfall case was 10.7 mg/L; the new value was 7.6 mg/L. With regard to estimates of peak storage salinities for the Serpentine Reservoir, the difference between mined and unmined scenarios was 5.6 mg/L for the original report and was 4.3 mg/L for the addendum. These were reductions of 25%.

Also of interest in the addendum were the very low salinity differences between mined and unmined states for the low rainfall case. Some concern had been expressed that the low streamflows corresponding to the low rainfall case could result in a lack of water to dilute mining related groundwater discharge. The simulation results indicated otherwise; this rainfall case had a peak salinity difference of only 0.1 mg/L for inflow salinities to the Serpentine Reservoir.

4.6.3 Data collection for modelling

Details are provided below of those organisations involved in data collection, together with the issues they investigate.

1. Water and Rivers Commission (W&RC): Collection and management of streamflow, stream quality, rainfall and meteorological data, for catchment studies into mining and other forest management activities. Catchment scale estimations of Leaf Area Index (LAI).
2. CSIRO: Remote sensing methods for determination of catchment LAI.
3. MARCAM Consulting (Dr. J Marshall): Field determination of LAI for jarrah forest and bauxite mine revegetation, vegetation water use in forest, and different ages of rehabilitation.

4. Alcoa: Hydrographic plotting of all historic bore and stream data; continued collection and management of groundwater, soil salinity and relevant hydrogeological data within experimental catchments.

Discussions have been held to initiate an extended post-graduate study programme at UWA into soil moisture characteristics in the Darling Range generally and bauxite mining and rehabilitation areas specifically. This will commence in 1998.

4.7 Vegetation studies

The evolution of computer modelling for the prediction of the effects of bauxite mining in the Darling Range has moved progressively towards the development of distributed models which seek to reflect the physical hydrological processes of the system. The significance of the plant water relations in the hydrological cycle has become increasingly evident and extensive investigations have been undertaken in the period 1990 to date.

4.7.1 Water use of the Jarrah forest

The transpiration rates of dominant and sub-dominant jarrah trees within Del Park catchment were monitored for a two year period from 1990 using the heat pulse technique. This study estimated that the annual transpiration rate for trees in the intact forest in 1992 was 542 mm compared with the annual rainfall of 1 271 mm; the transpiration rates reach just above 2 mm per day in summer (Marshall and Chester 1992).

The effect of an intense thinning treatment (removal of 84% of the basal area) on annual transpiration rate was assessed at Hansen catchment. The study found that seven years after thinning, the water use by the thinned forest was about one third that of the intact forest; the remaining trees individually were using about twice as much water as their intact forest counterparts (Marshall and Chester 1992). The enhanced vegetation water use is believed to be caused by additional water uptake by the dominant (mainly jarrah) trees, as well as by the sub-dominant middle storey trees (e.g. *Allocasuarina fraseriana* and *Banksia grandis*), and by coppice growth of jarrah. The coppice growth is a new component produced following forest thinning. Understorey plants (shrubs, sedges, etc.) were noticeably unresponsive to the thinning of the trees (Marshall pers comm.).

Using energy balance and heat pulse methods, the evapo-transpiration from intact jarrah forest was studied intensively for 10 day periods in spring and summer 1993/4 (Silberstein *et al.* 1998); this gave data for periods of minimum and maximum water stress when atmospheric evaporative demand was high. The study site was in the IRZ at the meteorological station established in the Gordon catchment. Energy balance techniques estimate the total evapo-transpiration from the intact forest; this includes evaporation from soil, free water on the leaves and transpiration of all plants. The results of this study found that the forest maintained high leaf conductances during summer. The data indicated that the forest stand had sufficient access to water in the deep regolith to sustain near-potential evapo-transpiration rates throughout the year. On average, the total water use of the trees was slightly, but not significantly, greater in summer than spring (2.8 mm day^{-1} and 2.5 mm day^{-1} respectively). Summer soil evaporation rates were about half the spring rates (Silberstein *et al.* 1998).

4.7.2 Water use by revegetated mined areas

Research has been directed at quantifying the water use by revegetation of different ages, to determine when it will approach that of the pre-mining forest.

The heat pulse method of measuring water use was applied for a year, from March 1993 to March 1994, to a bauxite minepit rehabilitated in 1989 (Marshall *et al.* 1996). The water use of twenty four shrubs and saplings from eleven species was measured. Water use of the entire rehabilitation vegetation was estimated from the measurements on individual plants and the projected cover of each species. The rehabilitation vegetation used 252 mm, or 23.2%, of the 1084mm of rain recorded during the year. This is less than by jarrah trees alone in an adjacent unmined forest, which used 42.6% and 33.6% of the rain that fell in 1989-1990 and 1991-1992 respectively (Marshall and Chester 1992; Marshall 1993). At the end of the heat pulse study the area was excavated to assess the root distribution of the vegetation, which showed that the tree roots were colonising old root channels and should have been able to access water stored deep in the soil profile. However, the root area index was low compared with the pre-mining forest and this would have contributed to the lower water-use on the rehabilitated site. The other major factor was its lower LAI; the LAI of the adjacent forest site was estimated as 1.6 during a previous study (Ruprecht *et al.* 1987), whereas the LAI of the rehabilitated site was only 0.61 (Marshall *et al.* 1996). Water use per unit area of crown varied between species, depending on crown structure (Marshall *et al.* 1996). Water use per unit ground area was lower for shrubs with spreading crowns such as *Acacia* species; the highest water use was by saplings of *Eucalyptus* species that have columnar crowns and a high LAI. In the hotter, drier months species with deep root systems tended to increase their water use relative to shallow-rooted species.

In December 1995 the LAIs of eight rehabilitated areas were estimated. Four 2 m x 2 m quadrats at each site were harvested and the area of leaves determined. There was no clear relationship between the age of the rehabilitation and LAI. The LAIs of all these sites were higher than that of the site studied by Marshall *et al.* (1996) and many are similar to that of the forest site measured by Ruprecht *et al.* (1987). Shallow-rooted shrubs dominate the LAI of young rehabilitated areas whereas in older areas the eucalypts dominate. Transpiration rates on rehabilitated mined areas should increase with time, as more roots of the major tree species are able to access water stored deep in the regolith. It appears that the water use of this vegetation will approach that of the pre-existing forest by about 15 years.

4.7.3 Estimation of the Leaf Area Index of forest sites

In forests, LAI has been identified as a critical determinant for quantifying the evapo-transpiration rates; the higher the LAI the higher the evapo-transpiration rates. However, LAI is very difficult to measure in the field and to estimate for the large areas used in catchment studies. Whitford *et al.* (1995) assessed three methods, allometric, hemispherical photography and LANDSAT, of indirectly estimating the LAI of a forest site in the IRZ. The estimate of LAI from an allometric relationship was not significantly different from the direct estimate measured by harvesting the leaves but the method is very time consuming and only suitable for small areas of <0.5 ha. The hemispherical photography technique was found to be more suitable for annual monitoring studies but is limited to areas of <5.0 ha, still well short of the area of a typical experimental catchment (>100 ha).

Wallace (1996) developed a significant statistical correlation between spectral data from LANDSAT Thematic Mapper (TM) and LAI for 38 upland jarrah forest sites, estimated using the hemispherical photography method. The hemispherical photography values ranged from just above zero to 3.5. The regression results indicate that the LAI of upland jarrah forest can be estimated by LANDSAT with a residual standard error of approximately 0.4 units for sample areas of 0.25 ha. This method is now used to estimate the LAI of forest in all hydrological research catchments monitored as part of the JIRZRP.

5. Further research and implications for future management

5.1 Further research

5.1.1 Catchment studies

Considerable allocation of resources has been directed toward data collection on the catchments intended for the experimental mining exercise, the two small scale catchments Cameron West and Central, and the Jayrup medium scale demonstration catchment. To improve the quality of input data for the WEC-C model, Jayrup catchment will have a number of bedrock definition and groundwater-level bores installed in 1998. Pre-mining monitoring of the hydrology of the three catchments has started and will give data relating to pre-mining operations such as logging, as well as to mine development activities and to the actual mining and rehabilitation operations.

Baseline studies of streamzone ecology were conducted in the Cameron and Jayrup catchments in 1997 (StreamTec, 1997). The data from this study will constitute the basis of future work identifying possible ecological effects of mining on the streamzone ecology.

To fulfil the research obligations of Alcoa with regard to mining in the IRZ, the focus of the JIRZRP will now remain on the three catchments referred to above. Related studies, including validation of predictive models, will continue on a number of HRZ catchments, particularly those which have undergone changes or have been subjected to disturbance likely to influence the hydrological processes. Such catchments include the thinned Hansen, Higgens and Jones catchments of the Conjurunup Brook, and the mined and rehabilitated catchments of Lewis, Warren and Bennetts. Monitoring of long term mined catchments such as Seldom Seen, More Seldom Seen and Del Park will continue to provide more complete patterns of hydrological recovery as their rehabilitation progresses.

The ongoing JIRZRP hydrometric monitoring network was rationalised in December 1997 and the key monitoring stations are now: Seldom Seen, More Seldom Seen, Waterfall Gully, Del Park, Lewis, Bates, Warren, Bennetts, Cameron West, Cameron Central, Gordon, Gordon meteorological station, Jayrup and Big Brook.

5.1.2 Predictive modelling

The development of the fully distributed WEC-C model provides a sound basis for simulating a range of potential IRZ mining scenarios: from the partial crusher operation represented by the Jayrup proposal; to an entire crusher and mining operation within the IRZ, and its potential impact on a water supply reservoir. The WEC-C model is presently limited on PC type computers to a catchment size of about 100 km^2, though by the year 2000 this should have increased to 500 km^2. Developing and promoting models capable of simulating catchments of larger size will be encouraged. The LASCAM model presently fills this role and will be developed further to become more suitable for JIRZRP research. A variant of WEC-C will be developed to operate at these larger scales. Both model developments will place great demands on data collection.

A critical requirement during 1998/9 will be the validation of WEC-C against a range of other treated catchments for which post treatment hydrological data are available. As an initial step in this process, and as a means of facilitating mining access within a defined time frame, the model will be used to predict the longer term streamflow responses within the Hansen, Higgens and Jones catchments. These catchments were subjected to a range of silvicultural thinning operations during the mid 1980s but have not yet demonstrated complete recovery to pre-thinning streamflows. WEC-C can therefore be validated against the data gathered to date and, provided an acceptable match is produced, can be used for the longer-term predictions of recovery.

The WEC-C model will also be applied, and reapplied, to the mining catchments of Del Park and Seldom Seen. Its use will also be encouraged on other, non-mining, studies in the south-west such as agricultural clearing studies in the Collie catchment.

5.1.3 Vegetation studies

As models, particularly WEC-C and LASCAM, have evolved, there has been a requirement for greater definition of the water use of vegetation in the native forest and following treatments such as logging and mining. Having developed an understanding of the undisturbed forest and revegetation of different ages, the areas of vegetation now identified for greater scrutiny are swamps and streamzones within the jarrah forest system. Bauxite mining rarely directly disturbs these, but their role in influencing hydrological processes may be of greater significance than hitherto believed; perhaps, too, any influence may display significant seasonal variability. Research programmes are in place to study the swamps and streamzones in detail.

Research into the remote estimate of vegetation cover by LANDSAT is considered vital to the JIRZRP. Both LASCAM and WEC-C use distributed LAI as a key model input and it is known that variations in LAI are one of the most significant variables effecting streamflow and stream salinity. Improvement is required in LANDSAT estimation of LAI for all vegetation types in the natural forest of upslope, lowerslope and streamzone areas, and in revegetated mine areas.

5.1.4 Regional studies

During the next five years investigations will be carried out into the applicability of a number of different techniques to better predict the salinity risk of potential bauxite areas in the IRZ and LRZ. Data collection techniques to be investigated include: LANDSAT, air-borne and surface geophysics, aerial photography, and geomorphological attributes derived from mapping studies.

5.2 Implications for future management

The JIRZRP has two clearly identified objectives, (Croton and Dalton, 1994a). The second of these relates specifically to considerations of management of mining operations within the IRZ. It states that the programme will *"document the forest, mine and rehabilitation management practices which should be used in the intermediate rainfall zone"*.

It is significant to note that the simulations undertaken to date have only reflected Alcoa's existing well-established mine development, mine planning and rehabilitation techniques and operations. The results indicate that, for the scale of operations in the IRZ reflected in the simulations, no changes to existing practice are merited.

It will be an essential component of the JIRZRP to undertake simulations of future IRZ mining scenarios having a potential for greater impact on the quality of water resources. In the event that such simulations indicate unacceptable adverse effects, alternative management strategies will have to be developed and built into subsequent simulations.

It is understood that the development of any management strategies and practices as an alternative to those already in place will be the primary responsibility of Alcoa, rather than of the JIRZRP researchers as a group. Clearly the research group as an entity will be required to endorse any proposals for change designed to overcome hydrological impacts, before they are considered for implementation.

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