Water Authority
of Western Australia

WATER RESOURCES DIRECTORATE

Measurement and Modelling of Water and Salt Balances on Small Catchments

Report No. WH 18

April 1986

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Hydrology Branch

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CONTENTS

1. INTRODUCTION

1.1 Background to the Study

Bauxite mining began in the Northern Jarrah Forest in 1963 when Alcoa of Australia Limited opened its first mine near Jarrahdale. Since that time, Alcoa's operations have expanded rapidly and 3382 ha of Jarrah Forest has been cleared for mining (DCE, 1984).

To date Alcoa has confined its mining operations to the High Rainfall Zone (HRZ, above 1100 mm mean annual rainfall) within the Jarrah Forest. Research conducted by Alcoa and various government departments has shown current mining to be safe with respect to stream salinisation owing to the low concentration of salts in the soils and groundwaters of this zone.

Alcoa has made a legal undertaking not to begin routine mining in the eastern part of its mineral lease until further research has shown that such an operation would not result in an unacceptable increase in stream salinity. This undertaking reflects some concern about the effects of mining soil profiles containing relatively high concentrations of salt. Any significant increase in groundwater recharge caused by mining in these areas may lead to salt mobilisation and consequent increases in stream salinity.

Attention has focussed on the Intermediate Rainfall Zone (IRZ, 900-1100 mm mean annual rainfall) as most of the bauxite reserves in the eastern part of Alcoa's lease lie within this zone. Since the mid-1970's it has been envisaged that a trial mining experiment in tha IRZ would be necessary to assess the effects of mining operations on the hydrologic regime. Investigations for the selection of bauxite research catchments within the IRZ have been underway since 1979.

At the present stage of the Bauxite Hydrology Research Programme (BHRP), research is planned at three different scales:

(i) hillslope;
(ii) small catchment; and
(iii) regional/water resource catchment.

In 1983 the Catchment Research Group (CRG) was formed for the purpose of assessing the hydrological impact of bauxite mining operations at the small catchment scale. This role was expanded in 1985 to include the regional/water resource catchment component of the BHRP. During its first year of operation, the CRG concentrated on the selection of proposed trial mining and control catchments within the IRZ. Preliminary instrumentation on these catchments came into operation during 1985, and a period of analysis, assessment and review will commence this year (1986).

1.2 Case for a Trial Mining Experiment

The research methodology described in this report is based on the execution of a trial mining experiment in the IRZ. From a small catchment perspective, there are several arguments in favour of carrying out this experiment. They are:

(i) it is the most direct way of assessing the impact of mining operations within the IRZ;

(ii) there is little experience with land use changes of this type in the IRZ;

(iii) hydrological process studies necessary for the construction of realistic catchment model structures are reliant on the experiment taking place;

(iv) it is the best way of validating the predictive capabilities of catchment models; and

(v) there are substantial difficulties in extrapolating the impact of any type of land use change from the environment of the HRZ to that of the IRZ.

An important argument against the trial mining experiment relates to the question of variability over the IRZ. The proposed experiment requires the allocation of considerable resources to one site. These resources could be spread over a number of sites covering a wide range of conditions. While this argument has merit, the spreading of resources may limit our knowledge of hydrologic processes within the IRZ. This will in turn affect the detection and modelling of the changes in hydrological processes induced by bauxite mining. Therefore, there are many benefits to be gained by conducting the trial mining experiment.

1.3 Outline of this Report

The purpose of this report is to establish a methodology for the measurement and modelling of hydrological processes on small catchments. A regional research methodology and an overall research strategy for the CRG will be described in separate reports.

A statement of the main objectives of the small catchment research programme and a general description of the required tasks are given in the next Section. The catchment experiments that are currently operated or planned by the CRG are described in Section 3. Section 4 examines the hydrological catchment processes that need to be monitored in the field. Emphasis is placed on the type of instrumentation required and on the role of other BHRP groups in small catchment research. Section 5 describes the issues involved in the deterministic modelling of hydrological processes on a catchment scale, outlines a proposed deterministic modelling methodology, and discusses the role of paired catchment studies and statistical modelling in the CRG's research activities.

1.4 Acronymns and Abbreviations

This report makes substantial use of a number of acronyms and abbreviations for the sake of brevity. Acronyms and abbreviations used in the report are collected for convenient reference in Appendix A.

1.5 Acknowledgements

Thanks are due to all members of the CRG for their constructive criticisms of earlier versions of this report.

2. OBJECTIVES AND TASKS

2.1 Main Objectives

The main objectives of the CRG's small catchment research programme are:

(i) to develop a quantitative understanding of the hydrological processes that occur on small catchments within the IRZ. This includes the spatial and temporal variations of these processes and their interrelationships;

(ii) to assess the appropriateness of alternative mining and rehabilitation strategies. Of particular interest is the effect of bauxite mining on the quantity and quality of streamflow and groundwater; and

(iii) to determine the impact of bauxite mining on the spread and/or intensification of dieback disease, and to determine the effects of dieback disease and forest management practices on water resources.

2.2 Tasks

In order to meet the above objectives, Alcoa has used two statistical analyses to identify a set of experimental catchments that have terrain and vegetation characteristics, salt storage levels and bauxite reserves which are typical of those encountered within the IRZ. The trial mining catchment and at least one control catchment will be chosen from this set. For the trial mining and control catchments, the tasks to be undertaken by the CRG may be summarised as follows:

(i) the integration of relevant information on:

(a) vegetation
(b) the location and areal extent of dieback disease;

(c) the location and areal extent of the mining operation within the boundary of the trial mining catchment;
(d) the nature of the soil and salt content profiles from unweathered bedrock to the land surface; and
(e) catchment surface and bedrock topography;

(ii) the installation of instrumentation for the:

(a) measurement of the quality and quantity of rainfall and runoff;
(b) detection of subsurface lateral flow, and the measurement of its dynamics, areal extent and quality;
(c) measurement of groundwater level, flow and quality, and hydraulic parameters;
(d) measurement of the dynamics of identified runoff source areas; and
(e) measurement of spatial and temporal variations in salt storage over the life of the research project;

(iii) the establishment of regular field surveys over the life of the project to monitor major changes in:

(a) crown cover and leaf areas;
(b) the level of dieback disease; and
(c) the hydraulic properties of the soil profile (pre-mining, mining and post-mining).

(iv) a review of existing catchment models. This review should include a literature survey and the application of a small subset of these models to rainfall and runoff data collected from the IRZ and its surrounds. The latter may help to identify modelling approaches that meet the requirements of the CRG, and thus provide a basis for the design of new model structures;

(v) the development of new catchment models which give a more realistic representation of the hydrological and salt transport processes observed in the IRZ; and

(vi) the use of the new catchment models to:

   (a) assess the effects of bauxite mining operations on catchment response (water and salt outputs) sometime after the rehabilitation of the mine pits in the trial mining catchment;
   (b) predict the effects of mining operations on the hydrological processes in other catchments;
   (c) provide means of assessing the appropriateness of alternative minesite and/or forest management practices;
   (d) contribute to the development of regional computer models; and
   (e) provide guidelines for the type and number of field measurements required.

The level of attention paid to other catchments within the IRZ will be largely determined by the financial and manpower resources available at any given time, and by the needs of the regional component of the CRG's research programme.

2.3 Liaison with other Groups

It can be seen from the above discussion that close liaison with other Working Groups within the BHRP is essential if the catchment studies are to proceed in an efficient manner. At all times the members of the CRG should be aware of the techniques and instrumentation used by other Groups, and be prepared to participate in collaborative studies. Thus the remainder of this report will highlight areas in which inputs from other Working Groups are desirable, and describe several experimental studies at the catchment scale that will be of benefit to more than one Group.

3. DESCRIPTION OF RESEARCH CATCHMENTS

3.1 Introduction

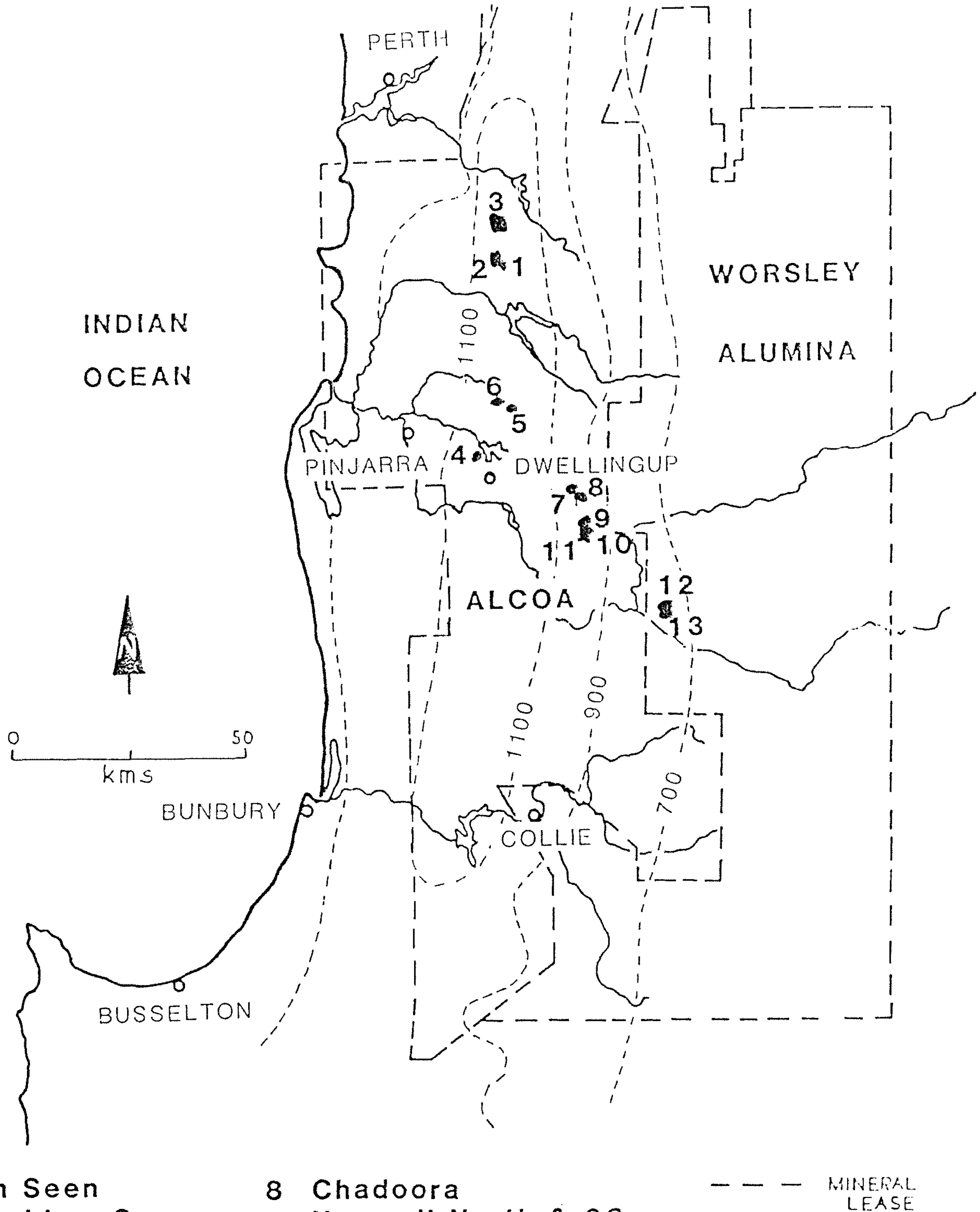
The purpose of this Section is to give a brief description of research catchments that are of direct interest to the CRG. These catchments lie within the High, Intermediate and Low Rainfall Zones of the Northern Jarrah Forest. Most of the information given in this Section is based on the work of Loh et al. (1984), PWD (1984) and Stokes (1984).

3.2 High Rainfall Zone Catchments

Six bauxite research catchments have been established in the High Rainfall Zone (HRZ). The general location of the catchments is shown in Figure 3.1, and their precise locations, characteristics and instrumentation are given in Tables B.1 to B.6, (see Appendix B).

Since the commencement of Alcoa's operations in the HRZ, complete mining operations have taken place on Seldom Seen and More Seldon Seen catchments, (see Table B.1 and B.2). These catchments, together with the forested Waterfall Gully catchment (see Table B.3), were established with the aim of identifying the effects of different silvicultural treatments on the quanitity and quality of streamflow.

The Del Park catchment (see Table B.4) has already been partially mined and rehabilitated. An unmined hillslope within the catchment is presently being utilised by the HPG as a testing ground for soil moisture monitoring equipment in the jarrah forest environment. In addition a continuing study of the groundwaters within the catchments is being conducted by Alcoa. However, there is doubt as to the value of the catchment in determining the effects of mining on hydrological processes since the catchment is unpaired and was partially mined shortly after establishment.



1 Seldom Seen
2 More Seldom Seen
3 Waterfall Gully
4 Del Park
5 Higgens
6 Lewis
7 Pindalup
8 Chadoora
9 Yarragil North & 6C
10 Yarragil East
11 Yarragil 4X
12 Bee Farm Road
13 Tunnel Road

— — — MINERAL LEASE

------ ISOHYET (mm)

Figure 3.1 Catchment Location Diagram
After Loh et al., 1984

Higgen's catchment (see Table B.5) is to be used to study the effect of a 'western style' mining rehabilitation treatment on hydrological processes operating within the HRZ. Lewis catchment (see Table B.6) is to be used as a control for Higgen's catchment.

It is envisaged that the HRZ catchments will be of value to the catchment modelling activities of the Group (see Section 5.2.6). However, there is at present no intention of increasing the level of instrumentation on these catchments.

3.3 Intermediate Rainfall Zone Catchments

Six bauxite research catchments have been established in the IRZ on the basis that their topography, vegetation, bauxite tonnages, salt storage, and stream salinity are typical of the region. The location of the catchments is shown in Figure 3.1, and their characteristics and instrumentation are given in Tables B.7 to B.12.

Initially, two catchments in the Pindalup area (Pindalup West and Chadoora) were instrumented for rainfall and streamflow quantity and quality in early 1984. However, these catchments have little or no dieback and were thus considered not to be fully representative of conditions in the IRZ. Further investigations have led to the establishment of four catchments in the Curara Block. These catchments have significant dieback infections in their valleys.

Three out of the four Curara Block catchments (Yarragil 4X, 5D and 6C) have been operated by CALM since 1976. The existing weir at 5D has been replaced by a new weir some 200 metres downstream, and the new catchment named Yarragil East. The instrumentation at the existing weirs on 6C and 4X has been upgraded and may be replaced.

The gauging station site for the fourth Curara Block catchment (Yarragil North) is approximately 950 m upstream of the weir at 6C. The station on Yarragil North was commissioned in July 1985. (A temporary station 53.5 m upstream of the present site was operated from July 1984 to July 1985).

At present it is intended to use Yarragil East and/or Yarragil 4X as a control for the proposed trial mining catchment (Yarragil North - 6C). The nesting of the Yarragil North and 6C catchments will provide an important opportunity to study the effects of bauxite mining on the hydrologic regime at two different length scales. Moreover, there is some evidence that little streamflow occurs at the gauging station site on Yarragil North under present hydrological conditions. Therefore, the gauging station at 6C may prove to be a valuable back-up for the station at Yarragil North, particularly during the pre-mining phase of the BHRP.

Forest research projects are also planned for the IRZ. It has been proposed that the Yarragil 4X catchment (see Figure 3.1) be used to assess the effect of forest thinning on vegetation and hydrological processes in the zone (Stokes, 1984). The earliest date for the initiation of this experiment is the summer of 1986/87 (R.A. Stokes and G.L. Stoneman, pers. comm.). Alcoa, however, have requested that the option of using Yarragil 4X as a control for the trial mining catchment be kept open until 1988. This possible conflict of interest can be avoided by close liaison between Group members.

Other catchments may be selected for forest thinning experiments at a later date. One proposal is to use one or both of the Pindalup catchments for these experiments. However, it is preferable that the Pindalup catchments should remain intact for at least five years. This will provide a better definition of the hydrologic variability of the IRZ and an opportunity to develop a number of worthwhile data sets for catchment model validation (see Section 5.2.3). Moveover, some flexibility is maintained in case bushfires destroy the usefulness of the Curara Block catchments or future investigations reveal Yarragil North not to be a suitable trial mining site. Similarly, Yarragil East should only be used as a control for the 6C catchment, and should not be used for forest thinning experiments unless the Curara Block is abandoned.

3.4 Low Rainfall Zone Catchments

Two research catchments have been established in the Low Rainfall Zone. The general location of the catchments is shown in Figure 3.1, and their precise locations, characteristics and instrumentation are listed in Table B.13 and B.14. As shown in Figure 3.1, the catchments are in the vicinity of Mount Saddleback which lies within the area designated by Worsley Alumina's mineral lease.

The Mount Saddleback catchments were initally instrumented by the Public Works Department (PWD) to facilitate the study of the effects of bauxite mining operations on a low rainfall environment with relatively unusual geologic and topographic features (Stokes, 1984). These catchments will provide an early opportunity for the CRG to test its ability to detect a change in hydrological processes caused by bauxite mining operations. A preliminary analysis of the data collected from these catchments has been presented by Stokes (1983). However, research in this rainfall zone will be given a lower priority than that for the trial mining experiment owing to the unique geology of Mt Saddleback, and the difficulties experienced in the installation and operation of the instrumentation.

4. MEASUREMENT OF CATCHMENT PROCESSES

4.1 Introduction

Land use research at the catchment scale involves the study of the complete land-phases of the hydrologic and the salt cycles. Therefore, it is necessary to measure water and salt inputs, outputs and storage to form water and salt balances. The purpose of this Section is to present an experimental methodology for measuring the variables which significantly affect these balances. These variables include rainfall and saltfall, interception and throughfall, infiltration, soil moisture and salt storage, evapotranspiration, surface and subsurface flows, and groundwater storage.

4.2 Rainfall

Although the catchments described in Section 3 are relatively small, large spatial variations in measured rainfall at the same scale have been reported in the literature (see, e.g., Jackson, 1969). These variations may be due to factors such as topography, elevation, the orientation of storm tracks, and the presence of vegetation. If mean rainfall (daily, weekly or monthly, etc.) is to be correctly determined, then it is essential that the density of the rain gauge networks be sufficient to accurately measure the spatial variations in rainfall over the catchments. Therefore, optimisation of the rain gauge networks on the research catchments is desirable.

Shih (1982) has presented a statistical procedure for determining the number of gauges needed to estimate the mean rainfall with a given confidence level to achieve a specified accuracy. The procedure is more tractable than the stochastic approaches described by Rodriguez-Iturbe and Mejia (1974) and Lenton and Rodriguez-Iturbe (1977) for example, and recognizes the constraints that forested catchments place on gauge locations. Application of the procedure to ungauged catchments involves:

(i) the design and installation of a temporary rain gauge network (a minimum of four gauges per catchment is required);

(ii) the collection of rainfall data at the required time interval (day, week, month, etc.); and

(iii) the application of Shih's rainfall variation analysis to the data. This analysis produces plots of number of gauges versus level of statistical accuracy, and indicates how the rain gauges should be allocated within the catchment boundary.

Consequently, four Water Authority pluviographs (recording rain gauges) have been installed on the Yarragil 6C catchment. The rainfall data collected from this temporary network will enable the preparation of a rational rainfall gauge network for the 6C catchment, and provide guidelines for designing networks for Yarragil East, Pindalup West and Chadoora catchments. The use of pluviographs is necessitated by the remoteness of the trial mining site and the need to have daily rainfall data for modelling purposes.

N J Schofield (pers. comm.) has advised that the HPG may conduct a comparative test of standard Water Authority pluviograph installations against ground level recording rain gauges as used by the Institute of Hydrology (UK). If the ground level gauges prove to be more accurate than and at least as reliable as the standard gauges, ground level gauges will be used by the CRG. All rainfall data for the BHRP will be collected and processed by the Water Authority.

4.3 Saltfall

The quantification of the salt balance of a catchment requires the measurement of the concentration of salt in incident rainfall and dryfall (bulk precipitation). Bulk precipitation collectors vary in design complexity from a simple open container to collectors equipped with vapour traps, overflow bottles, bird discouragers, and insect filters (Galloway and Likens, 1978).

A simple collector suitable for the Darling Range environment has been developed and successfully tested by the CSIRO (Williamson et al., 1977). The collector is a storage rain gauge with a fibreglass funnel, insect screen and an air vent which prevents air locks in a polyethylene storage vessel. This design achieves satisfactory evaporation suppression and does not contaminate the collected water.

The bulk precipitation collectors have been placed adjacent to the pluviograph sites in the Yarragil 6C and East catchments. The gauges were sampled at fortnightly intervals during the winter of 1985 and the network optimisation precedure described in Section 4.2 will be applied to the saltfall data. Thus rational saltfall gauging networks can be constructed for the Yarragil catchments and an assessment made of the sampling interval required for modelling purposes. The saltfall data will be collected and processed by the Water Authority.

4.4 Interception and Throughfall

Schofield (1984) has presented a method for the detailed measurement of interception and throughfall at the hillslope scale. Although the method cannot be realistically applied to the catchment scale, the results obtained will be of value of the CRG. In particular, it is expected that the HPG's study of interception and throughfall will yield valuable information on the effectiveness of different vegetation species to intercept rainfall.

Although gross changes in the forest canopy can be monitored by aerial photography, it is desirable to have information on seasonal changes in leaf area obtained by ground reconnaissance methods. At present these methods have a high manpower requirement. However, recent technological advances suggest that this requirement will be substantially reduced in the near future. It is also expected that officers from CALM will be able to provide assistance and results form their interception and throughfall experiments.

4.5 Infiltration

As noted by Schofield (1984), the sprinkling infiltrometer is perhaps the best means of measuring infiltration rates for process studies at the hillslope scale. This is also likely to be true for similar studies at the catchment scale and thus close liaison with the HPG will be sought. Manpower for the experiments could be obtained from interested tertiary students.

Although high spatial variability in infiltration capacity can be expected over a catchment, the results of infiltrometer experiments will provide estimates of the mean and variance of this capacity. This information is vital to the successful calibration of physically based catchment models.

4.6 Soil Moisture Storage

An important component of the water balance in the Jarrah Forest is soil water storage. As the soil water storage capacity of a relatively undisturbed catchment could be substantially decreased by bauxite mining operations, changes in runoff generation and groundwater recharge processes might be expected.

Spatial and temporal changes in soil water storage on a catchment basis can be readily monitored by a neutron logging network. Guidelines for the determination of network density and the location of neutron access tube sites have been provided by the AWRC (1974). In regard to network density, the AWRC recommend the use of about 15 x 6m access tubes since this is the approximate maximum number of tubes that can be sampled in any given day.

However, a preliminary analysis of soil moisture data for the Dal Park Area C instrumented hillslope suggests that access tube lengths in excess of 6 m may be required in Darling Range research catchments if soil moisture storage is to be accurately assessed (Schofield et al., 1985). Long access tubes (>6 m) cause many difficulties in fabrication and installation, and increase logging time. Therefore, careful consideration should be given to the number and length of the neutron access tubes to be installed in the trial mining and control catchments. This will require the acquisition and examination of data on the location and extent of various soil and vegetation types, and topographic features.

4.7 Salt Storage

Salt storage is an important component of the salt balance and as such it should be continuously monitored during the pre- and post-mining phases of the BHRP. Although existing soil salt profiles can be obtained from chemical analyses of Alcoa's drill cores, further substantial drilling operations will disturb vegetation and the soil profile. Moreover, once a core has been taken, soil salinity can never again be sampled at the same point.

Schofield (1984) has indicated the intention of the HPG to install vertical arrays of soil salinity sensors to detect vertical solute fluxes. If this instrumentation proves to be successful, sensor profiles should be installed to measure salt movement on a catchment basis. This would probably involve a sensor profile network of similar density to that for neutron logging.

4.8 Evapotranspiration

Although an understanding of the process of evapotranspiration is essential to the construction of catchment models, the CRG has neither the expertise nor the resources to become involved in evapotranspiration research. Therefore, the CRG will rely heavily on the results of evapotranspiration research presently conducted by the Evapotranspiration Working Group, Alcoa, CALM, CSIRO and the Water Authority, and published evapotranspiration models and relationships.

4.9 Surface Runoff

Surface runoff can be defined as that portion of rainfall which, during or immediately following a storm, ultimately appears as streamflow in the channel network of a catchment (Huggins, 1982). This streamflow may be due to overland flow, emergence of soil water into stream channels, channel precipitation, and direct precipitation onto swamps and other saturated areas.

The quantity and quality of surface runoff generated by the Yarragil North, 6C and East catchments will be monitored at three new gauging stations. Gauging stations for Yarragil North and East catchments are now operational and the upgraded station for Yarragil 6C should be commissioned before the winter of 1986. The occurrence of underflow beneath the gauging station weirs will be detected by monitoring water levels in nests of piezometers placed adjacent to the weir walls.

Observations in the Jarrah Forest by several researchers have revealed that a large portion of surface runoff is generated by variable source areas. The behaviour of these areas is dynamic, and thus continuous measurement of their extent is desirable. This can be achieved by installing grids of shallow, automated tensiometers around permanently saturated areas. Unfortunately, the cost of commercially available automated tensiometers is quite high and this may preclude the experiment. However, M G Hodnett from the Institute of Hydrology, Wallingford, has advised that the Institute's automated tensiometer design could be easily modified to substantially reduce capital costs without adversely affecting tensiometer performance. The feasibility of manufacturing these instruments is being explored by the HPG.

4.10 Throughflow

When a soil profile contains an impeding layer, infiltrated water may form an ephemeral, perched zone of saturation (Amerman and Naney, 1982). As the zone of saturation builds up on top of the impeding layer, saturated throughflow and saturated overland flow may occur. Throughflow under unsaturated conditions and flow within preferred lateral pathways known as 'pipes' are also known to occur (Chorley, 1978). Investigations by Stokes and Loh (1982) have revealed that over 90% of Salmon catchment streamflow is due to these runoff generation mechanisms.

Since shallow, lateral subsurface flow is to be studied in detail by the HPG (Schofield, 1984), the role of the CRG is to establish the importance of this flow component (in terms of its quantity and quality) relative to that of surface runoff and groundwater flow in the Yarragil catchments. This could be achieved by judicious placement of automated tensiometers and piezometers within the catchment boundaries. The piezometers will also be useful for water quality sampling.

4.11 Groundwater Systems

One of the principal components of any water balance study is a hydrodynamic analysis of the groundwater system. Such an analysis requires knowledge of the hydraulic properties of the aquifer(s) involved. These together with estimates of groundwater recharge or discharge, can be determined by:

(a) pumping tests;
(b) flow-net analyses based on contour maps of the piezometric surface indicated by a network of observation wells; and
(c) applying parameter estimation techniques to groundwater models.

Pumping tests in the Yarragil catchments will be conducted by personnel from Geological Survey & Alcoa, and other members of the CRG will give assistance if required. The number and location of the tests should be decided at future meetings of the CRG.

Since the contour maps of the piezometric surface are derived from water level readings taken from an observation well network, the geometry of the network is of utmost importance to any groundwater study. The network should be of sufficient density to permit accurate assessemnt of groundwater storage, lateral and vertical recharge, and discharge. Increasing attention has been given to the application of geostatistical techniques to optimal observation network design (see, e.g., Szidarovszky, 1983; Carrera et al., 1984; Virdee and Kottegoda, 1984). However, these techniques are still subject to intense research and have not yet become a matter of routine. Therefore, there is some justification for establishing grids of observation wells on the basis of professional judgement. These grids can be modified in the future after a review of preliminary water level data.

Another aspect of flow-net analysis which deserves consideration is the frequency of piezometric level observations. A sampling interval of once a month is recommended at the beginning of the water balance study. After a period of observation, the reduction in the accuracy of the groundwater level time series caused by a decrease in the sampling frequency can be assessed and a new sampling interval adopted. However, it may be necessary to increase the sampling interval to twice a month during key months of the water year in order to identify the peaks and troughs of observtion well hydrographs.

A major limitation of a pumping test is that aquifer parameters are only determined in the vicinity of the pumping well. In contrast, the estimation of aquifer parameters by solution of the inverse problem offers a means of determining regional parameter estimates. However, the fundamental instability of the inverse problem (Allison and Peck, 1985) and the observation that, for a given point in an aquifer, different values for the same aquifer parameters can be obtained from different models (Bear, 1979) has prevented groundwater model calibration from becoming a routine means of aquifer parameter estimation. Therefore, it would appear that conducting a number of pumping tests over the area of interest is the most practical means of determining aquifer parameters.

The study of groundwater quality requires the collection of water samples at regular intervals from selected observation wells. The water quality variable of principal interest to the BHRP is total soluble salt. It is recommended that a monthly sampling interval over a two year period be adopted for a small number of key wells within the trial mining and control catchments. This should give sufficient information to enable the assessment of an appropriate sampling frequency.

5. MODELLING OF CATCHMENT PROCESSES

5.1 Introduction

One of the principal tasks of the CRG is the development of computer models which operate at the small catchment scale. These models should:

(i) be capable of simulating the hydrological processes that occur within the IRZ;

(ii) be capable of assessing and forecasting the effect of localised bauxite mining operations on hydrological processes; and

(iii) have the simplest possible structure whilst maintaining adequate performance.

It is unlikely that any one model or modelling approach will fulfil all of these criteria. Therefore, it is envisaged that the modelling activities of the CRG will simultaneously proceed along three lines:

(i) deterministic modelling;
(ii) paired catchment studies; and
(iii) statistical modelling.

This Section outlines a proposed catchment modelling strategy for the CRG. It includes a review of the following aspects of deterministic modelling practice:

(i) model selection;
(ii) parameter definition;
(iii) calibration and validation;
(iv) prediction uncertainty; and
(v) scenario evaluation.

Brief discussions of paired catchment studies and statistical modelling are presented since the principles of the former are relatively simple and well-known, and work on the latter has reached an advanced stage.

5.2 Deterministic Modelling

5.2.1 Model selection

All hydrological models involve some degree of simplification of reality. This simplification arises from lack of knowledge and field data, and computational constraints (Beven and O'Connell, 1982; Mein and McMahon, 1982). The consequences of simplification are:

(i) model outputs will never be identical to observed outputs even if field measurements are free of errors;
(ii) more than one model may give equally good results;
(iii) for any given model, different sets of parameter values may produce similar model performances;
(iv) different models may rate more or less highly in different applications; and
(v) complex models may not necessarily give superior results to simpler models.

Catchment models can be classified according to their model structure. Three broad categories are generally recognised:

(i) lumped models;
(ii) distributed models; and
(iii) quasi-distributed models.

Lumped models do not consider the spatial variability of catchment characteristics or hydrological inputs (e.g. rainfall, saltfall, etc.). These quantities are usually averaged over the entire catchment area. Hydrological processes are generally represented by different functional forms based on approximate flow equations and intuition. Lumped models also primarily rely on the comparison of simulated and observed catchment outputs for the estimation of model parameter values. There are a large number of lumped models with varying degrees of complexity available. Examples include the models of Crawford and Linsley (1966), Boughton (1966), and Burnash et al. (1973).

In contrast, distributed models treat a catchment as being a continuously variable system over time and space. They use the general nonlinear partial differential equations for the processes of mass and energy transfer within the catchment continuum. These equations are solved by approximate numerical techniques such as finite differences or finite elements. Examples of distributed models include the Systeme Hydrologique Europeen (SHE) model described by Beven et al. (1980) and the Institute of Hydrology Distributed Model, IHDM, presented by Morris (1980). Despite their complexity, distributed models have a number of limitations:

(i) they are based on empirical process laws (Darcy's Law) and uniform flow equations (Manning or Darcy-Weisbach equations);

(ii) they involve a degree of lumping of processes at the model grid or mesh scale which is often larger than the scale characteristics of processes;

(iii) they do not necessarily include all relevant physical processes (e.g. the SHE model neglects soil water hysteresis and lateral unsaturated flow); and

(iv) they involve considerable expenditure in terms of computer resources, data preparation and field measurement.

Quasi-distributed models attempt to bridge the gap between lumped and distributed models. They involve the subdivision of the catchment into relatively homogenous subareas which are treated as lumped units. Hydrological processes are described by conceptual functional relationships like those used in lumped models, and therefore lumped and quasi-distributed models are subject to similar limitations. However, they do allow additional hydrological data to be incorporated into the calibration process. In some instrances, the values of model parameters can be determined on the basis of field measurement alone (see Beven and Kirkby, 1979). Further examples of quasi-distributed models include the Monash Model (Porter and McMahon, 1971), the WATSIM model (Aston et al., 1980), and the Darling Range Catchment Model (DRCM) developed by the Metropolitan Water Authority (Perth).

Given the wide range of catchment models available, it can be seen that the selection of a particular model or even a model type for the BHRP is not an easy one, and must be based on economic and time constraints as well as the requirements of the CRG.

Beven and O'Connell (1982) have argued that physically-based distributed models should be used whenever it is necessary to forecast the effects of a localised land use change. By physically-based they mean firmly based in the present understanding of the physics of the processes which control the hydrological behaviour of catchments.

Given the constraints on the CRG, it is the author's opinion that the Group does not have the resources to undertake the development of a new physically-based distributed model for the BHRP. Therefore, if this type of model is to be used by the CRG, it may be necessary to enter into a commercial agreement with the model developers or their agents. It should be emphasised that to the author's knowledge most if not all of these models do not contain solute transport algorithms that are of use to the Group. The incorporation of the algorithms into this type of model would be a major undertaking, one in which the developer may express little interest.

Therefore, it would appear that the CRG should concentrate its attention on quasi-distributed models. A review of currently available models of this type has failed to identify a catchment model which has all of the features considered necessary for the BHRP. These features are:

(i) an overall modelling philosophy which obeys the Principle of Parsimony (Beck and Arnold, 1977), i.e., a more complicated model should be used only if there is overwhelming evidence that a simpler model cannot explain the observed data;

(ii) a model structure which is consistent with our present understanding of hydrological processes within the Darling Range, and which allows explicit representation of bauxite mining operations;

(iii) simulation of the salt balance;

(iv) model parameters which have a direct physical significance and that are measureable in the field (see Section 5.2.2); and

(v) conceptual elements with smooth response properties (see Section 5.2.3).

Thus there is a real need for the CRG to become involved in model development. The author believes that this development should not be initially limited to any particular model owing to our present lack of knowledge of hydrological processes in the IRZ. This position can be altered once a model structure appropriate to the IRZ can be perceived from the data collected by field instrumentation.

5.2.2 Parameter definition

The coefficients, exponents and constants in the equations describing the processes that have been incorporated into the model are its parameters. If the model is to be used to forecast the hydrologic effects of bauxite mining operations on ungauged catchments, it is essential that the model parameters have a distinct physical meaning. That is, they can be determined by direct or indirect measurement.

Few models satisfy this criterion. Most have parameters which must be solely determined by manual or automatic optimisation techniques. For these models the selection of parameter values for catchments that have undergone a land use change can only be made on the basis of subjective judgement. This can lead to significant bias in the parameter estimates unless the model user has had vast experience with the model.

Until recently, little research effort has been given to the development of catchment models with parameters that are determinable in the field. This situation is partly due to the observed spatial variability of hydrologic parameters and the lumped nature of most catchment models. Also, field measurement programs can have sizeable financial and manpower requirements if the number of parameters is large. Nevertheless, work by Aston and Dunin (1979) and Beven et al. (1984) has demonstrated that field measurement of model parameter values is feasible and that these values can be used to derive adequate simulations of streamflow time series.

It should be emphasised that field measurements are subject to sampling and measurement errors. Some workers have found that the error variance associated with such measurements may be relatively large (e.g. Keisling et al., 1977), and that single measurements may not provide an adequate estimate of the spatial average value of a parameter. Several measurements, however, will help to define the range of a given parameter and to detect data deficiencies.

There are two other factors worthy of consideration (see Beven and O'Connell, 1982). The first is that point measurements will only represent independent samples from the underlying population of parameter values if the spatial autocorrelation of the parameter is small relative to the distance between samples. Otherwise, the spatial pattern of the measurements must be considered in the determination of parameter values. The second is that whenever possible, field experiments should be conducted at similar length scale to that used in the model. For example, an estimate of saturated hydraulic conductivity obtained from a pumping test is preferable to one determined from laboratory tests on drilling cores. This follows from the theory of geostatistics which suggests that as the sampling volume of a quantity (measurement scale) increases the sampling variance will decrease.

Finally, careful consideration must be given to the selection of field measurement sites. It is impractical to consider a field measurement programme based on a fine grid of sampling points covering the entire area of Alcoa's mining lease. Instead, field measurement sites should be strategically placed to enable the use of spatial interpolation techniques such as Kriging (see Kafritsas and Bras, 1981) or Laplacian smoothing splines (see Hutchinson, 1984). For a given parameter, these techniques can be used to derive a contour map of estimated parameter values together with their estimation variances. This information would allow the application of the model to ungauged catchments between measurement sites, and estimates of the likely prediction errors in the model output caused by parameter uncertainty, (se Section 5.2.4). It is conceivable that information of this type would also be of great value to the regional research component of the BHRP.

5.2.3 Calibration and validation

Many modellers have used optimisation techniques to determine parameter values in order to avoid the problems associated with field measurements (e.g. spatial heterogeneity, measurement scale and cost). That is, initial parameter estimates are adjusted until the model output fits observed hydrologic outputs (usually streamflow) to the satisfaction of the model user. This process is often called 'calibration', and involves the use of either manual trail and error or automatic optimisation techniques.

Calibration of catchment models is usually viewed as a curve fitting exercise and as such it is appropriate for studies which require the extension of streamflow records, the generation of runoff statistics or the assessment of the effects of land use changes on the hydrologic regime. It is, however, unsuited to the requirements of the BHRP which involve the study of parameter variations over space and time. Reliable parameter estimates (i.e. estimates close to the true value with low variability) are required for forecasting the effects of land use change, and there are several well-documented reasons why unreliable estimates may arise from curve fitting (Ibbitt and O'Donnell, 1971; Johnston and

Pilgrim, 1976; Mein and Brown, 1978; Posada and Bras, 1982; Sorooshian and Gupta, 1983). They are:

(i) highly-parameterised models are likely to have pairs of parameters that interact strongly with one another;

(ii) the objective function can be indifferent to the values of inactive (threshold-type) parameters;

(iii) the non-convexity of the response surface can lead to the presence of discontinuities and local optima;

(iv) poor quality input data can bias parameter estimates (Dawdy and Bergmann, 1969; Singh and Woolhiser, 1976); and

(v) deficient model structures may lead to parameter estimates that are intrinsically different to their counterparts measured in the field. In some cases, the estimates can take on physically unrealistic values.

Factors (i), (ii) and (iii) can cause considerable difficulty in converging to an optimum of the objective function. Although over-parameterised models can fit observed data well with high coefficients of determination, the parameters and the predictions of these models will be characterised by high levels of uncertainty. This is unacceptable for studies involving the effects of a localised land use change. However, the adoption of a parametrically efficient model with smooth rather than segmented functional relationships can do much to alleviate the problems normally associated with catchment model calibration.

As far as factor (iv) is concerned, the catchments involved in the BHRP should have sufficient instrumentation to ensure the production of high quality hydrological data. Thus it is hoped that (iv) will have little effect on the performance of catchment models.

In contrast, factor (v) is a cause for concern. A deficient model structure can only be detected during the validation phase of the modelling exercise. Validation involves the testing of the model's forecasting ability on data other than those used in model structure identification and calibration. If the model output is an accurate simulator of this test data, then the model is considered to have conditional validity (Mein and McMahon, 1982; Young, 1983). That is, a fit to field data does not necessarily imply that the model struture is correct (Gardner et al. 1980). Validation is a continuous process in that the model should be reassessed in the light of future developments and additional data (Young, 1983).

5.2.4 Prediction uncertainty

As noted earlier, complex catchment models have large explanatory potential and can often be fitted readily to scant time series data. However, the application of sensitivity analysis to these models reveals that the fitted parameters are ill defined and that only a small parameter subset is important in explaining the observed catchment behaviour. As a result, the hydrologic predictions obtained from the 'calibrated' model are characterised by a high degree of uncertainty. Clearly, there is an optimum which trades off the greater potential prediction accuracy from a complex mdoel with the parsimony and greater precision of parameters obtained from a simple model.

Regardless of the size of the catchment model finally adopted by the CRG, it is considered essential that effort be made to determine confidence limits around the model predictions due to the uncertainty (variance) in the parameter estimates. There are two basic approaches to this task. The first is deterministic sensitivity analysis in which the sensitivity of the model predictions to variations in the parameter values over their specified range is investigated (see, e.g., McCuen, 1973; Coleman and De Coursey, 1976). The second is stochastic sensitivity analysis in which sensitivities are calculated in relation to parameters defined in terms of statistical probability distributions (see, e.g., Gardner et al., 1980; Garen and Burges, 1981).

Of the two basic approaches to sensitivity analysis, stochastic methods are generally considered to be superior to their deterministic counterparts (Gardner et al., 1980; Young, 1983). Examples of these methods include first-order analysis and the Monte Carlo method (see Dettinger and Wilson, 1981). Monte Carlo simulation is a generally accepted means of quantifying the effects of parameter error propagation through a model. First-order analysis, on the other hand, is an approximate method which gives reasonable results when the response surface in the vicinity of the optimum parameter set is approximately quadratic. However, the computational requirements of first-order analysis are far less burdensome than those for the Monte Carlo approach. Moreover, first-order methods have been found to give reasonable estimates of the prediction uncertainty caused by parameter error for a wide range of nonlinear hydrologic models (e.g. Garen and Burges, 1981; Townley and Wilson, 1983; Bates and Townley, 1985).

5.2.5 Scenario evaluation

Once the model has been formulated and successfully validated, it can be used in a planning role to investigate the hydrologic effects of various bauxite mining and rehabilitation practices. At this stage the quasi-distributed nature of the model and the physical basis of its parameters will assume particular significance. However, the model predictions should be qualified by estimates of the uncertainty due to parameter error.

5.2.6 Proposed strategy for deterministic catchment modelling

Faced with the situation described in Sections 5.2.1 to 5.2.5, a procedure for the application of a new model to a particular catchment might be as follows:

(i) compute the means and variances of the model parameter values obtained by field measurement;

(ii) estimate the parameter values by calibrating the model on half of the observed hydrologic output time series. This can be achieved by using a computer package similar to that developed by Kuczera (1983);

(iii) compute the estimation covariance matrix using the parameter estimates obtained from (ii);

(iv) test the null hypothesis that the parameter values obtained by field measurement and calibration come from the same underlying population. If the null hypothesis is accepted then (v), otherwise revise the model structure and field measurement programme and repeat steps (i) to (iv); and

(v) test the model on the remaining half of the observed hydrological output time series. If necessary, modify the structure of the model and repeat steps (i) to (v) until satisfactory performance is achieved.

Steps (i) to (v) can be applied to research catchments which have not been subjected to a land use change. Mining operations on the 6C catchment should not proceed until it has been demonstrated that the model has conditional validity. This can only occur if there is sufficient data for model calibration and validation. Mein and McMahon (1982) cite several examples where Australian workers have found that 2.5 to 5 years of good quality data (without gaps) are required for model calibration. This implies that trial mining should not commence until 5 to 10 years after the start of the rainfall-runoff record.

Approximately five years after the mining and rehabililation of the Yarragil 6C catchment, the forecasting ability of the model for the new hydrologic regime should be tested. Thus another field measurement programme should be instigated during this period to determine a new set of parameter values. These values and their variances can then be used in a prediction uncertainty analysis to obtain modelled streamflow time series (quality and quantity) with appropriate confidence limits. If the corresponding observed time series fit within these limits then the model can be accepted as a reasonable simulator of the catchment's hydrologic behaviour. Otherwise, the model structure should be modified and the entire validation procedure repeated until satisfactory agreement is achieved.

5.3 Paired Catchment Studies

Section 5.2 has emphasised the important role of deterministic catchment models in the BHRP. It must be admitted however, that the success of this modelling effort cannot be guaranteed. Mein and McMahon (1982) and others have expressed doubts about the ability of catchment models to forecast the effects of land use change. Certainly, there have been few if any published results of independent tests of this predictive capability.

Consequently, there is a need to have other sources of information on the hydrologic effects of bauxite mining operations. One source is a paired catchment experiment in which the Yarragil East and/or Yarragil 4X catchment acts as a control for Yarragil 6C. Thus the hydrological responses of these catchments will be correlated prior to bauxite mining, and the change in the correlation after mining used as an indicator of the effects of the land use change.

While paired catchment experiments can yield much valuable information, the results are somewhat site specific and cannot be used to indicate the likely effects of different mining and rehabilitation practices. To overcome these limitations, it would be necessary to conduct an expensive factorial experiment involving several paired catchments. This approach is regarded as being unfeasible for the CRG at the present time.

5.4 Statistical Modelling

Another source of information on the hydrologic effects of bauxite mining operations is the application of statistical modelling techniques to hydrological data. Generally, this approach involves the calibration and validation of a statistical model on all pre-mining data. At some point in time after mining, the calibrated model can be used to generate hydrologic time series that could be expected to occur had mining not taken place. The effects of bauxite mining can then be assessed by comparing the synthetic and observed time series form the date of mining to the date of analysis.

Tsykin (1983, 1984, 1985a,b) and Tsykin and Slessar (1985) have successfully applied a nonlinear multiple regression technique to a number of hydrologic data sets collected in Alcoa's mineral lease area. The technique gives good least squares fits to the observed data as indicated by the high coefficients of determination during model calibration and validation.

A feature of the statistical approach is the possibility of including predictor variables that are affected by mining operations (e.g. terrain characteristics, salt storage, and indexes of forest condition). There is also a possibility of extrapolating regression equations for one catchment to another after applying corrections for differences in conditions between the calibration and extrapolation environments (Tsykin, 1985c).

6. CONCLUSIONS AND RECOMMENDATIONS

The foregoing discussion has described a research methodology for the identification of the hydrologic effects of bauxite mining on small catchments within the Intermediate Rainfall Zone. It has highlighted the need for hydrological process and modelling research, and the importance of the trail mining experiment to the proposed research programme.

It is apparent that a high level of field instrumentation will be required over the length of the study. It is highly desirable that the data collected from this instrumentation be properly utilised. Therefore, the density of instrumentation networks and monitoring frequencies should be continually reviewed. Instrumentation involving considerable capital and running costs should not be installed until the selection of the trail mining and control catchments is finalised.

It is also evident that some of the field experiments described in Section 4 have high manpower requirements. These experiments may be suitable research projects for postgraduate students, and it is suggested that educational institutions could be approached with this view in mind.

The deterministic, paired catchment and statistical approaches to catchment modelling have been described in Section 5. All have their own set of advantages and limitations, and it is essential that research along these three lines be continued. With respect to deterministic modelling, it is recommendad that the CRG proceed with the development of a quasi-distributed catchment model. The Group should not attempt to develop a distributed model unless the performances of quasi-distributed and currently available distributed models are found to be inadequate. It is also essential that catchments representing atypical conditions in the IRZ be examined during deterministic and statistical modelling studies.

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APPENDIX A

ACRONYMS AND ABBREVIATIONS

AWRC	Australian Water Resources Council
BHRP	Bauxite Hydrology Research Programme
CALM	Department of Conservation and Land Management
CRG	Catchment Research Group
CSIRO	Commonwealth Scientific and Industrial Research Organization
DCE	Department of Conservation and Environment (Western Australia)
HPG	Hillslope Processes Group
HRZ	High Rainfall Zone
IRZ	Intermediate Rainfall Zone
MWMG	Minesite Water Management Group
PWD	Public Works Department of Western Australia

APPENDIX B

CATCHMENT DETAILS

TABLE B.1

DETAILS OF CATCHMENT ON SELDOM SEEN CREEK - TRAVELLERS ARMS (After PWD, 1984)

AWRC No.	616021
River Basin	Swan Coast
Location	Latitude S 32° 14'59" AMG. Grid N 6431500 Longitude E 116° 05'15" E 50 414050

CATCHMENT CHARACTERISTICS

Catchment Area	7.53 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1250 mm/annum
Pan Evaporation	1750 mm/annum
Geomorphology	Low relief; undulating plateau, lateritic soils over Archean granitic and metamorphic rocks.
Landforms	Map Units; DCE (1980) 65% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 35% - Yarragil Upland Valleys; gentle slopes of gravelly duplex soils and sands, orange earths in valley floor.
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, blackbutt in valleys; severely affected by dieback (rehabilitation in progress).
Clearing	More than 15% catchments cleared and mined - most to be rehabilitated.
Landuse	State Forest reserve and mining tenement.
Regulation	None - water holes dug for extractions during summer, some mine pits.

GAUGING STATION DETAILS

Period of Record	March 1966 to date.
Establishment	Land Use Research Catchment (Water Authority of W.A.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Sharp crested V weir for control of all flows.
METEOROLOGICAL NETWORK	2 pluviographs (No. 509269 and 509325) in operation from June 1974 to date and May 1976 to May 1983 respectively.
WATER QUALITY	Fresh; average TSS value of 140 mg/L.
PIEZOMETER NETWORK	0 piezometers.

TABLE B.2

DETAILS OF CATCHMENT ON MORE SELDOM SEEN CREEK - CERIANI FARM
(After PWD, 1984)

AWRC No.	616022
River Basin	Swan Coast
Location	Latitude S 32° 15'18" AMG. Grid N 6430890 Longitude E 116° 04'43" E 50 413220

CATCHMENT CHARACTERISTICS

Catchment Area	3.27 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1275 mm/annum
Pan Evaporation	1750 mm/annum
Geomorphology	Low relief; undulating plateau, lateritic soils over Archean granitic and metamorphic rocks.
Landforms	Map Units; DCE (1980) 50% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 50% - Yarragil Upland Valleys; gentle slopes of gravelly duplex soils and sands, orange earths in valley floor.
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, blackbutt in valleys; severely affected by dieback
Clearing	More than 15% cleared and mined - most to be rehabilitated.
Landuse	Mainly State Forest and mining tenement.
Regulation	None - water holes dug for extractions during summer, some mine pits.

GAUGING STATION DETAILS

Period of Record	April 1966 to date.
Establishment	Land Use Research Catchment (Water Authority of W.A.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Sharp crested V weir control all flows.
METEOROLOGICAL NETWORK	1 pluviograph (No. 509270) in operation from June 1974 to date.
WATER QUALITY	Fresh; average TSS value of 150 mg/L.
PIEZOMETER NETWORK	0 piezometers.

TABLE B.3

DETAILS OF CATCHMENT ON WATERFALL GULLY - MOUNT CURTIS
(After PWD, 1984)

AWRC No.	616023
River Basin	Swan Coast
Location	Latitude S 32° 12'29" AMG. Grid N 6436090 Longitude E 116° 04'44" E 50 413210

CATCHMENT CHARACTERISTICS

Catchment Area	8.74 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1275 mm/annum
Pan Evaporation	1770 mm/annum
Geomorphology	Low to moderate relief; undulating to dissected plateau, lateritic soils over Archean granitic and metamorphic rocks.
Landforms	Map Units; DCE (1980) 10% - Cook Monadnocks; hills generally mantled with laterites, some have rock outcrop. 50% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 30% - Yarragil Upland Valleys; gentle slopes of gravelly duplex soils and sands, orange earths in valley floor. 10% - Murray Incised Valley; moderate slopes, red and yellow earths, some rock outcrop
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, blackbutt in valleys; severely affected by dieback
Clearing	No significant permanent clearing.
Landuse	State Forest reserve.

GAUGING STATION DETAILS

Period of Record	April 1966 to date.
Establishment	Land Use Research Catchment (Water Authority of W.A.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Sharp crested V weir control all flows.

METEOROLOGICAL NETWORK	1 pluviograph (No. 509271) in operation from June 1974 to date.
WATER QUALITY	Fresh; long term average TSS value of 140 mg/L.
PIEZOMETER NETWORK	0 piezometers.

TABLE B.4

DETAILS OF CATCHMENT ON SOUTH DANDALUP TRIBUTARY - DEL PARK
(After PWD, 1984)

AWRC No.	614007
River Basin	Murray River
Location	Latitude S 32° 40'06" AMG. Grid N 6385060 Longitude E 116° 02'27" E 50 410060

CATCHMENT CHARACTERISTICS

Catchment Area	1.33 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1300 mm/annum
Pan Evaporation	1680 mm/annum
Geomorphology	Moderate relief; dissected plateau with lateritic soils over Archean granitic and gneissic rocks.
Landforms	Map Units; DCE (1980) 55% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 45% - Yarragil Upland Valleys; sandy gravels on slopes, orange earths on swampy valley floor.
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, some blackbutt in valleys
Clearing	No permanent clearing, but some 35% of catchment has been progressively mined in three pits and later rehabilitated.
Landuse	Experimental catchment in State Forest reserve and mining lease.
Regulation	None apart from mine pits.

GAUGING STATION DETAILS

Period of Record	May 1974 to date.
Establishment	Land Use Research Station (Bauxite mining - CSIRO.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.
METEOROLOGICAL NETWORK	1 pluviograph (No. 509263) and 1 pluviograph and 1 evaporimeter (No. 509393) in operation from May 1974 and October 1979 to date, respectively.
WATER QUALITY	Fresh; average TSS value of 130 mg/L. Automatic Pumping Sampler in operation from October 1977 to date.
PIEZOMETER NETWORK	158 piezometers monitored at different time intervals.

TABLE B.5

DETAILS OF CATCHMENT ON LITTLE DANDALUP TRIBUTARY - HIGGEN'S CATCHMENT

(After PWD, 1984)

AWRC No.	614020
River Basin	Murray River
Location	Latitude S 32° 35'02" AMG. Grid N 6394450 Longitude E 116° 05'15" E 50 414380

CATCHMENT CHARACTERISTICS

Catchment Area	0.710 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1300 mm/annum
Pan Evaporation	1670 mm/annum
Geomorphology	Low relief; undulating plateau, lateritic soils over Archean granitic and gneissic rocks.
Landforms	Map Units; DCE (1980) 55% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 45% - Yarragil Upland Valleys; sandy gravels on slopes, orange earths on swampy valley floor.
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, severely affected by dieback disease.
Clearing	No significant permanent clearing - various forest management techniques.
Landuse	Experimental catchment in State Forest reserve.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	June 1977 to date.
Establishment	Land Use Research Station (Forest hydrology - CALM.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.
METEOROLOGICAL NETWORK	1 pluviograph (No. 509348) in operation from June 1977 to date.
WATER QUALITY	Fresh; average TSS value of 120 mg/L.
PIEZOMETER NETWORK	0 piezometers.

TABLE B.6

DETAILS OF CATCHMENT ON WILSON BROOK TRIBUTARY
- LEWIS CATCHMENT

(After PWD, 1984)

AWRC No.	614021
River Basin	Murray River
Location	Latitude S 32° 34'06" AMG. Grid N 6396140 Longitude E 116° 03'41" E 50 411895

CATCHMENT CHARACTERISTICS

Catchment Area	1.70 km^2
Climate Zone	Mediterranean climate, high winter rainfall
Average Rainfall	1300 mm/annum
Pan Evaporation	1670 mm/annum
Geomorphology	Low relief; undulating plateau, lateritic soils over Archean granitic and gneissic rocks.
Landforms	Map Units; DCE (1980) 55% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 45% - Yarragil Upland Valleys; sandy gravels on slopes, orange earths on swampy valley floor.
Natural Vegetation	Map Units; Beard (1980) 100% Forest; jarrah-marri forest, severely affected by dieback disease.
Clearing	No significant permanent clearing - various forest management techniques.
Landuse	Experimental catchment in State Forest reserve.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	May 1977 to date.
Establishment	Land Use Research Station (Forest hydrology - CALM.)
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.

METEOROLOGICAL NETWORK	1 pluviograph (No. 509349) in operation from May 1977 to date.
WATER QUALITY	Fresh; average TSS value of 110 mg/L.
PIEZOMETER NETWORK	0 piezometers.

TABLE B.7

DETAILS OF CATCHMENT ON SOUTH DANDALUP TRIBUTARY - PINDALUP WEST

AWRC No.	614 043
River Basin	Murray River
Location (approx)	Latitude S 32° 44' AMG. Grid N 6377800 Longitude E 116° 13' E 50 427300

CATCHMENT CHARACTERISTICS

Catchment Area	6.89 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1030 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest reserve and mining lease.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	May 1984 to date.
Establishment	Land Use Research Station (Bauxite mining - Water Authority of W.A.).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.
METEOROLOGICAL NEIWORK	1 pluviograph (No. 509233) and 1 evaporimeter in operation from May 1974 to date.
WATER QUALITY	Automatic Pumping Sampler in operation from May 1984 to date. Continuous conductivity recorder in operation from May 1984 to date.
PIEZOMETER NETWORK	11 piezometers monitored monthly.

TABLE B.8

DETAILS OF CATCHMENT ON SWAMP OAK BROOK TRIBUTARY
-CHADOORA

AWRC No.	614 045
River Basin	Murray River
Location	Latitude S 32° 45'30" AMG. Grid N 6375300
(approx)	Longitude E 116° 15' E 50 430000

CATCHMENT CHARACTERISTICS

Catchment Area	4.63 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1000 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest reserve and mining lease.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	May 1984 to date.
Establishment	Land Use Research Station (Bauxite mining - Water Authority of W.A.).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.

METEOROLOGICAL NETWORK	2 pluviographs (No. 509235 and 509234) in operation from May 1974 to date.
WATER QUALITY	Automatic Pumping Sampler in operation from May 1984 to date.
PIEZOMETER NETWORK	10 piezometers monitored monthly and 1 multiport piezometer.

TABLE B.9

DETAILS OF CATCHMENT ON YARRAGIL BROOK TRIBUTARY
-YARRAGIL EAST

AWRC No.	614 050
River Basin	Murray River
Location	Latitude S 32° 50' AMG. Grid N 6367000
(approx)	Longitude E 116° 14' E 50 428260

CATCHMENT CHARACTERISTICS

Catchment Area	5.01 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1050 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest reserve and mining lease.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	July 1985 to date.
Establishment	Land Use Research Station (Bauxite mining - Water Authority of W.A.).
Gauging Installation	Float operated continuous L&S graphical recorder to data. Combination sharp crested V weir control all flows.

METEOROLOGICAL NETWORK	1 pluviograph (No. 509436) in operation from July 1985 to date.
WATER QUALITY	Automatic Pumping Sampler in operation from July 1985 to date.
PIEZOMETER NETWORX	12 piezometers monitored monthly.

TABLE B.10

DETAILS OF CATCHMENT ON YARRAGIL BROOK TRIBUTARY
-YARRAGIL 6C

AWRC No.	614 049
River Basin	Murray River
Location	Latitude S 32° 49'25" AMG. Grid N 6367000
(approx)	Longitude E 116° 13'40" E 50 427600

CATCHMENT CHARACTERISTICS

Catchment Area	4.58 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1050 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest reserve and mining Lease.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	July 1985 to date.
Establishment	Land Use Research Station (Bauxite mining - Water Authority of W.A.).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.
METEOROLOGICAL NETWORK	4 pluviographs (No. 509433, 509434, 509435 and 509437) in operation from July 1985 to date.
WATER QUALIIY	Automatic Pumping Sampler to be installed 1985/86.
PIEZOMETER NETWORK	9 piezometers monitored monthly and 1 multiport piezometer.

TABLE B.11

DETAILS OF CATCHMENT ON YARRAGIL BROOK TRIBUTARY
-YARRAGIL NORTH

AWRC No.	614 046
River Basin	Murray River
Location	Latitude S 32° 49'35" AMG. Grid N 6367750
(approx)	Longitude E 116° 14' E 50 427600

CATCHMENT CHARACIERISIICS

Catchment Area	2.23 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1050 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest reserve and mining lease.
Regulation	None.

GAUGING SIATION DETAILS

Period of Record	July 1984 to date.
Establishment	Land Use Research Station (Bauxite mining - Water Authority of W.A.).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Combination sharp crested V weir control all flows.
METEOROLOGICAL NETWORX	3 pluviographs (No. 509433, 509434 and 509435) in operation from July 1985 to date.
WATER QUALITY	Automatic Pumping Sampler installed July 1985.
PIEZOMETER NETWORK	6 piezometers monitored monthly.

TABLE B.12

DETAILS OF CATCHMENT ON YARRAGIL BROOK TRIBUTARY
-YARRAGIL 4X

AWRC No.	
River Basin	Murray River
Location (approx)	Latitude S 32° 50'35" AMG. Grid N 6365831 Longitude E 116° 13' 19" E 50 427190

CATCHMENT CHARACTERISTICS

Catchment Area	2.70 km^2
Climate Zone	Mediterranean climate, intermediate winter rainfall
Average Rainfall	1170 mm/annum
Clearing	No permanent clearing.
Landuse	Experimental catchment in State Forest Reserve.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	1976 to date.
Establishment	Landuse research catchment (Forest Hydrology - CALM).
Gauging Installation	1976-1983 : Float operated continuous Stevens F type graphical recorder to date. Combination V weir. 1984 to date : Float operated L&S graphical recorder.
METEOROLOGICAL NETWORK	3 mass raingauges read weekly from 1976. 1 pluviograph (No. 509236) in operation from April 1984 to date.
WATER QUALIIY	Manual sampling at different time intervals from 1976 to date.
PIEZOMETER NETWORK	12 piezometers monitored monthly.

TABLE B.13

DETAILS OF CATCHMENT ON MOORADUNG BROOK TRIBUTARY - TUNNEL ROAD

(After PWD, 1984)

AWRC No.	614011
River Basin	Murray River
Location	Latitude S 32° 57'46" AMG. Grid N 6352700 Longitude E 116° 28'24" E 50 450800

CATCHMENT CHARACTERISTICS

Catchment Area	2.07 km^2
Climate Zone	Mediterranean climate, medium winter rainfall
Average Rainfall	730 mm/annum
Pan Evaporation	1530 mm/annum
Geomorphology	Moderate relief; monadnocks on undulating plateau, lateritic soils over Archean metamorphic rocks.
Landforms	Map Units; DCE (1980) 30% - Cook Monadnocks; high hills mantled with laterites, some rock outcrop. 40% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 30% - Coolakin Minor Valleys; sandy, gravelly slopes, some rock outcrop, narrow alluvial valley floor.
Natural Vegetation	Map Units; Beard (1980) 70% Forest; jarrah-marri forest on plateau. 30% Woodland; Marri-wandoo woodland in valleys.
Clearing	No significant clearing as yet.
Landuse	Experimental catchment in State Forest and mining tenement.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	May 1975 to date.
Establishment	Land Use Research Catchment (Bauxite Mining - Public Works Department).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Sharp crested combination V weir control all flows.

METEOROLOGICAL NETWORK	2 pluviographs (Nos. 509304 and 509311) in operation May 1975 and June 1975 to date, respectively.
WATER QUALITY	Fresh; average TSS value of 340 mg/L. Water is highly coloured. Automatic Pumping Sampler in operation from May 1975 to date.
PIEZOMETER NETWORK	20 piezometers monitored at different time intervals.

TABLE B.14

DETAILS OF CATCHMENT ON MOORADUNG BROOK TRIBUTARY - BEE FARM ROAD

(After PWD, 1984)

AWRC No.	614012
River Basin	Murray River
Location	Latitude S 32° 57'03" AMG. Grid N 6354000 Longitude E 116° 28'24" E 50 450500

CATCHMENT CHARACTERISTICS

Catchment Area	1.81 km^2
Climate Zone	Mediterranean climate, medium winter rainfall
Average Rainfall	730 mm/annum
Pan Evaporation	1530 mm/annum
Geomorphology	Moderate relief; monadnocks on undulating plateau, lateritic soils over Archean metamorphic rocks.
Landforms	Map Units; DCE (1980) 10% - Cook Monadnocks; high hills mantled with laterites, some rock outcrop. 70% - Dwellingup Laterite Plateau; uplands - duricrust, gravels and sands over mottled clay soils. 20% - Coolakin Minor Valleys; sandy, gravelly slopes, some rock outcrop, narrow alluvial valley floor.
Natural Vegetation	Map Units; Beard (1980) 70% Forest; jarrah-marri forest on plateau. 30% Woodland; Marri-wandoo woodland in valleys.
Clearing	No significant clearing as yet.
Landuse	Experimental catchment in State Forest and mining tenement.
Regulation	None.

GAUGING STATION DETAILS

Period of Record	May 1975 to date.
Establishment	Land Use Research Catchment (Bauxite Mining - Public Works Department).
Gauging Installation	Float operated continuous L&S graphical recorder to date. Sharp crested combination V weir control all flows.
METEOROLOGICAL NETWORK	2 pluviographs (Nos. 509305 and 509312) in operation May 1975 and June 1975 to date, respectively.
WATER QUALITY	Fresh; average TSS value of 530 mg/L. Water is highly coloured. Automatic Pumping Sampler in operation from May 1975 to date.
PIEZOMETER NETWORK	21 piezometers monitored at different time intervals.