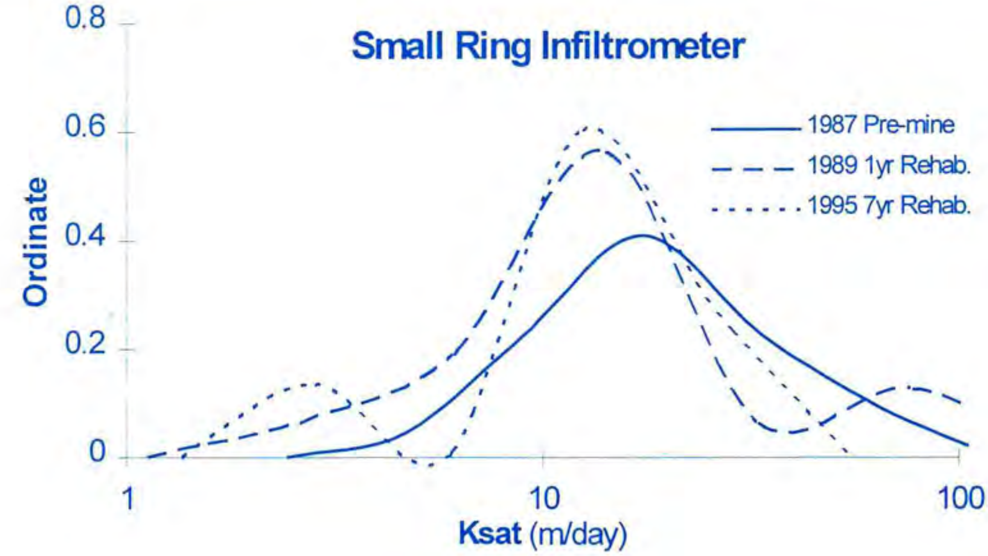
THE EFFECT OF BAUXITE MINING ON THE INFILTRATION CHARACTERISTICS OF DARLING RANGE SOILS



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THE EFFECT OF BAUXITE MINING ON THE INFILTRATION CHARACTERISTICS OF DARLING RANGE SOILS

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WATER AND RIVERS COMMISSION

REPORT SERIES

REPORT NO WRT 10 1997

Acknowledgements

We wish to thank Nick Schofield, John Ruprecht, Kelvin Baldock, Chris Gilbert, Leith Bowyer and all the others who undertook the field measurements. We would also like to acknowledge the help of Kevlin Baldock in answering dozens of questions about experimental methods and procedures without which the study couldn't have been completed. Thanks must also go to: Paul Raper and Jenny Dalton for their help in preparing the data sets, Jenny for help in editing the manuscript and Ben Croton for assistance in formatting the manuscript into final print format. For more information contact

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Reference Details

The recommended reference for this publication is: Croton, J.T. and Bari, M.A. 1997, *The effect of bauxite mining on the infiltration characteristics of Darling Range soils.* Water and Rivers Commission, Water Resource Technical Series No. WRT 10.

ISBN 0-7309-7283-6
ISSN 1327-8436

Text printed on recycled stock,
Onyx 100% recycled 100gsm
Cover, Media Satin 250gsm
January, 1997

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 to the east it merges 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 the last two can be undertaken without compromising the first there is an extensive research programme into the hydrology of the Darling Range. A component of this research has been the study of the water infiltration characteristics of near surface soils in the Del Park catchment and how these may be changed by mining and subsequent rehabilitation.

Determining the changes in infiltration characteristics due to mining is important for two reasons. Firstly, to estimate of the Probable Maximum Flood (PMF) for a mined catchment compared with unmined catchments and to determine whether spillway design criteria need revision. Under natural conditions, surface runoff from a Darling Range catchment is normally restricted to the area within and around the streamzone, with rainfall over the remainder of the area infiltrating and creating no direct runoff; this appears to be so even during extreme rainfall events. There is evidence that the situation may be different for mined and rehabilitated minepits.

Secondly, the Del Park catchment is a key component of the Joint Intermediate Rainfall Zone Research Programme (JIRZRP) in which bauxite mining and its likely impact on stream salinities of the Intermediate Rainfall Zone (IRZ) is being assessed. The JIRZRP stems from the commitment made by Alcoa of Australia Ltd. in their 1978 Environmental Review and Management Programme (ERMP) for the Wagerup Alumina Project 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 field measurements were made during four periods spread over nine years. In 1987 data were collected for the pre-mine forest soils on the Hillslope Transect within the Del Park catchment. In 1989, 1990 and 1995 post-rehabilitation data was collected from the Hillslope Transect. In 1990 data was also collected from two areas not on the Hillslope Transect. These were Mine Area A within the Del Park catchment, and an area south of Mine Area C and just beyond the Del Park catchment divide.

Three types of infiltration device were used. These were a ring infiltrometer of 300mm diameter, a well permeameter with a nominal hole size of 45mm and a disk permeameter. The disk permeameter was used only in 1995. The other two devices were used for each measurement period, 14 to 22 measurements being made in each set. The results were analysed for K_{sat} only. There was the potential in theory to determine sorptivity but this wasn't achievable in practice due to the high conductivities of the soils being tested.

It was concluded from the ring infiltrometer measurements that the hydraulic properties of the topsoil hadn't been changed by collection and respeading during the mining and rehabilitation operations. The mean surface infiltration rate had been reduced but this was probably related to the thickness of topsoil rather than to the topsoil properties. This finding is in variance from the observations of Huang, *et al.* (1996) who observed reductions in K_{sat} for forest soils in N.S.W. due to timber harvesting, Jorgensen and Gardner (1987) who observed an order of magnitude reduction in infiltration capacity due to mining in Pennsylvannia, USA and Sharma, *et al.* (1987) who found a reduction in soil surface infiltration capacity at Collie in the southern Darling Range, due to clearing for pasture.

The work by Sharma, *et al.* is directly comparable with the present study as the surface soils are similar. They found that the arithmetic mean K_{sat} was 20.8m/day for the forested catchment compared with 3.1m/day for the cleared catchment converted to pasture. The arithmetic mean for forested, pre-mine measurements in the present study is 21.2m/day. Why K_{sat} of the rehabilitated mine pit remains at a similar level to the pre-disturbance forest, while the area converted to pasture doesn't, is probably related to the deep tillage process used in mine rehabilitation in combination with the lack of trafficking, both animal and machine, of the rehabilitated mine areas compared with the pasture. In particular, the development and use of a "winged" tyne for Alcoa's bauxite mine rehabilitation has resulted in a system which is an order of magnitude more efficient for deep tilling the soil than a conventional chisel tyne (Croton - 1985). The whole profile to a mean wing depth of 1.4m is lifted by the wing of the tyne and subjected to shear and displacement forces which completely break-up any compaction and cementation. The study sites of Huang, *et al.* and Jorgensen and Gardner were not subjected to such a tillage process.

The well permeameter measurements showed a reduction in permeability at depth from 11m/day for the pre-mine case to 1 to 2m/day for the rehabilitated minepit cases. While this is a large reduction in permeability, it isn't sufficient to explain the observations of water ponded in mine areas after rainfalls of 100mm or less.

Ponding in rehabilitated minepits during significant rainfalls is probably due to the reduction in hydraulic conductivity once the base of the tillage zone is reached. Values from the literature give the K_{sat} for this layer to be of order 52mm/day. It is therefore highly likely that while the infiltration measurements reviewed in this report have improved our understanding of the hydraulic properties of near-surface rehabilitated minepit soils, they haven't defined the infiltration capacity of the control for runoff generation in rehabilitated minepits namely the conductivity of the mottled zone directly below the tillage layer. The direct use of the above infiltration data in the definition of runoff from a PMP type event could therefore result in an erroneous result. The data would, however, be useful in the definition of a layered, deterministic model of the system, which included the mottled zone beneath the tillage layer. Such modelling would fulfil the objectives of the study in that it would both aid PMF estimation and the hydrological studies of the JIRZRP. With regard to future studies, it was recommended that:

1. A well permeameter study of the hydraulic properties of the mottled zone directly beneath the tillage zone be undertaken. This study could be simplified by undertaking it in holes dug in mine areas prior to rehabilitation.

2. The results of the mottled zone properties study, in combination with other infiltration and soil properties data, be employed in a layered, deterministic model of the rehabilitated minepit soil profile.

1. Introduction

1.1 Background

The Darling Range in the south-west of Western Australia, consists of an undulating plateau bounded to the west by an escarpment and to the east it merges 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 the last two can be undertaken without compromising the first there is an extensive research programme into the hydrology of the Darling Range. A component of this research has been the study of the water infiltration characteristics of near surface soils in the Del Park catchment and how these may be changed by mining and subsequent rehabilitation.

Determining the changes in infiltration characteristics due to mining is important for two reasons. The first is for estimation of the Probable Maximum Flood (PMF) for a mined catchment and whether there is the need to revise spillway design criteria compared with unmined catchments. Under natural conditions, surface runoff from a Darling Range catchment is normally restricted to just the area within and around the streamzone, with rainfall over the remainder of the area infiltrating and creating no direct runoff. This appears to be the case even during extreme rainfall events. For mined and rehabilitated minepits the situation may be different. Croton and Tierney (1985) observed near surface interflow and direct runoff during storm events of less than 100mm which implies significant runoff from mined areas during extreme rainfall events.

The second reason why the study of infiltration characteristics of the Del Park catchment is being undertaken is because this catchment is a key component of the Joint Intermediate Rainfall Zone Research Programme (JIRZRP) in which bauxite mining and its likely impact on stream salinities of the Intermediate Rainfall Zone (IRZ) is being assessed. The JIRZRP stems from the commitment made by Alcoa of Australia Ltd. in their 1978 Environmental Review and Management Programme (ERMP) for the Wagerup Alumina Project 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 main participants within the JIRZRP are: Alcoa of Australia Ltd., Water & Rivers Commission (W&RC), Dept. of Conservation and Land Management (CALM). The programme is under the direction of the Bauxite Sub-Committee of the Steering Committee for Research on Land Use and Water Supply. The Bauxite Sub-Committee also includes representatives from CSIRO, Curtin University and University of Western Australia.

Croton (1990) reviewed all JIRZRP research and defined a programme to be followed. Croton and Dalton (1994) refined Croton's earlier programme and set a detailed work programme for the period up to 2020. They divided the programme into the eight study areas shown in Figure 1. The infiltration studies are part of the "Related Research and Processes Research" study area and are intended as inputs to small and large scale catchment modelling. A key component of this modelling work is the development of the WEC-C model and its application to the Del Park catchment. This work has been described by Croton (1995).

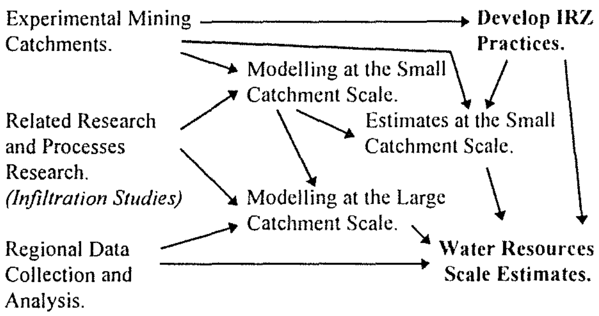

Figure 1: JIRZRP structure showing the "Infiltration Studies" in relation to the eight study areas of the programme.

1.2 Study Objectives

The objective of the study is to determine the impact of bauxite mining and rehabilitation on the infiltration characteristics of the near surface soils in the Del Park catchment near Dwellingup. Four sets of ring infiltrometer and well permeameter data have been recorded for the near-surface soils in 1987, 1989, 1990 and 1995. Ruprecht and Schofield (1989 and 1993) reviewed the results obtained during the 1987 pre-mining data collection programme. It is the intention of this study to review their findings and to compare them with the post-mining data. Data collection methods will be compared, and assessed for their applicability to Darling Range soils.

2. Description of the Darling Range and Bauxite Mining

2.1 The Darling Range

2.1.1 Topography and geology 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 2). The Darling Range is underlain by Precambrian igneous and metamorphic rocks which occasionally outcrop. Typical soil cover is 20 to 30m with weathered soils or saprolite (literally rotten rock) covering most of the landscape and with some sediments in the valley floors. Basement topography generally follows the surface topography although it is highly variable. Close to the Scarp the drainage is more incised, due to the higher rainfall and resultant streamflow, and the local relief is often greater than 100 m (Bettenay *et al.*, 1980).

In the western portion of the Darling Range, where the Del Park catchment is located, basement rocks are granitic gneisses and amphibolites with intrusive doleritic dykes (Bettenay *et al.*, 1980). 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 shallower than over granite.

As for much of the Australian continent, the combination of age and episodes of semi-arid climate has led to duplex soils with extreme textural contrasts and hydrologically complex soil profiles (Greacen and Williams, 1983). The basement rocks of the Darling Scarp have been deeply weathered and subjected to long periods of erosion. In the Darling Range a descriptive soil classification system of six morphological zones is used: superficial deposits, duricrust, mottled zone, pallid zone, weathering zone, and basement rock. A friable zone often exists between the duricrust and mottled zone but this is not generally discussed in the soil science literature. This zone is, however, 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 down a soil profile with distinct boundaries, though they sometimes grade into one another or alternate with depth.

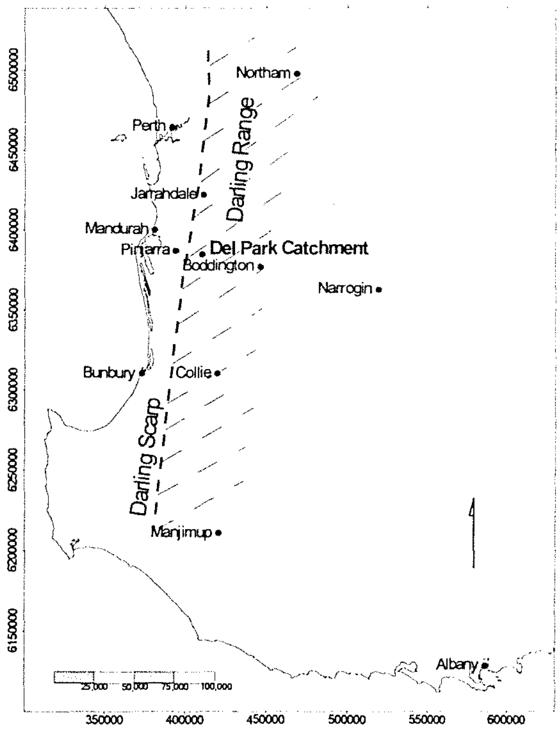

Figure 2: Locality plan showing the Darling Scarp, the Darling Range and the location of the Del Park catchment.

Surface soils range from sandy to loamy sands with some colluvial and alluvial deposits on the valley floors; many contain large percentages of sesquioxide gravels. Duricrusts are indurated rock-like materials composed of quartz and weathered rock fragments cemented together by iron and aluminium oxides. They are sometimes composed of cemented iron and aluminium nodules but are more usually massive or blocky in structure. There are commonly vertical holes through a duricrust layer, which are infilled with coarse sands, gravels and rock fragments (Ruprecht and Schofield, 1990). The thickness of the duricrust varies from zero to three metres but for areas of minable bauxite it is usually in the range one to two metres.

Mottled zone soils, which underlay the duricrust, are usually sandy clays, though those formed from dolerites usually have a higher clay content. Mottles of iron and aluminium oxides may be more abundant where duricrust grades into the mottled zone. The upper portion of the mottled zone often consists of an alumina rich friable zone which, in combination with the duricrust, forms the minable bauxite layer. Bauxitic layers can be found anywhere in the landscape except within the streamzone and their thickness can vary from zero to over 10m.

Below the mottled zone lie the white to buff clays or silty loams of the pallid zone. Pallid zone materials derived from granitic basement often contain quartz veins and other structures indicative of the rocks from which they are derived. The pallid zone grades into weathering zone in which the remnant fabric of the parent rock is still intact. Weathering zone generally has a significantly greater sand fraction than the pallid zone. In profiles derived from doleritic basement the weathering zone is often very thin or absent (McCrea, 1987).

In the Darling Range permanent groundwater occurs in the saprolite and within fractures in the basement rock. However, 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).

2.1.2 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 decreasing from west to east with distance from the coast. Average annual rainfall ranges from over 1,300mm/annum near the Darling Scarp to 450 mm/annum 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 rainfall intensities equivalent to 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 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.

2.1.3 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*). The dominant trees typically reach heights in excess of 30 m; due to much of the forest having been logged in the last 100 years, few taller 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 down 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. 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 Bauxite Mining

Bauxite mining in the Darling Range is a surface operation where alumina rich pods of ore of between two and 40ha 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 10m, though most mining occurs over the depth range three to four metres. The ore typically consists of the duricrust plus the friable layer which composes 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.

2. The surface soil and gravel layers above the duricrust, average thickness 400mm, are removed by scraper and either stockpiled or immediately spread on another mine area which is being rehabilitated. The top 50mm 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.

4. Front-end loaders place the ore into haul trucks which transport it to a central crusher.

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 Nichols, *et al.* (1985).

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 50mm of the forest soil remains on the surface.

4. The area is tilled using a "winged" tyne to an average depth of 1.4m (Croton - 1985) to promote surface water storage and infiltration and plant root penetration of the subsoils.

5. The areas are seeded with ground cover, shrub and tree species and fertilised. During the rehabilitation of the Del Park catchment trees were also planted by hand.

With regard to the aerial extent of mining, about 8,000ha have been cleared since mining commenced. The present clearing rate is about 500ha 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. Description of the Study Sites

3.1 The Del Park Catchment

The Del Park catchment is in the northern jarrah forest of the Darling Range and is located approximately 100km south of the city of Perth and 5km NNW of the township of Dwellingup (see Figures 2 and 3). The climate is Mediterranean, with the majority of the rainfall occurring in winter over the months of May to October inclusive. The long-term average annual rainfall for the catchment is estimated, from records for Dwellingup, to be about 1275mm. This places it within the high rainfall zone of the Darling Range. Annual pan evaporation is in excess of rainfall, with Dwellingup having an average of 1581mm for a standard Class A pan with data corrected to remove the effects of the bird guard.

The area of the Del Park catchment is 131ha. The stream at the outflow is of second order with a well defined stream channel. Within the catchment there are well defined swamp zones that are flat in comparison with the side slopes of the rest of the catchment (see Figure 3). Average side slope inclination at 10% is considered moderate. A permanent groundwater system covers virtually the whole of the catchment and intersects the soil surface in the stream areas.

Geologically, the catchment is located within the south western province of the Archaean Yilgarn Block. The primarily granitic bedrock has been divided by the intrusion of numerous sheet-like doleritic dykes that vary in thickness from a few millimetres to tens of metres. Deep in-situ weathering has produced a soil profile between 10 and 40m deep. On the side slopes, the soil profile consists of a surface soil sandy-gravel of zero to two metres depth, average 0.4m, overlaying a duricrust of zero to three metres thick, average about 1.5m; generally the duricrust is underlain by a mottled zone that includes an alumina rich friable layer which transitions into a deep, pallid, sandy-clay zone. The valley floor profile generally lacks the duricrust and is usually more silty in nature. Peat is commonly found in the swamp areas.

The catchment was fully forested prior to mining. The dominant overstorey species on the middle and upper slopes are jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) with bullich (*E. megacarpa*) and yarri (*E. patens*) on the lower slopes. The stream and swamp zones have a dense coverage of *Agonis linearifolia* and *Astartea fascicularis*.

There are three areas of bauxite mining within the Del Park catchment. These are known as Areas A, B and C and their locations are shown in Figure 3. Their total area is 46ha or 35% of the catchment area. Table 1 lists the clearing, mining and revegetation dates for mine areas.

Table 1: Clearing, mining and revegetation dates for mine areas A, B and C.

Mine Area	Clearing Dates	Mining Dates	Revegetation
A	July 75 to Dec. 75	April 76 to March 77	May 77 to June 79
B	July 76 to Sept. 77	July 77 to Sept. 78	July 78 to June 79
C	July 87 to Sept. 87	Oct. 87 to Dec. 88	Apr. 89 to June 89

In 1974 CSIRO installed a total of 74 groundwater piezometers in the catchment. Alcoa of Australia Ltd extended and upgraded this network and the total number of past and present piezometers, in and about the catchment, is now 160. The Water Authority of W.A. operates a 90° V, sharp crested weir at the catchment outlet. Parameters measured include continuous streamflow, rainfall and stream salinity.

3.2 The Study Sites in Detail

3.2.1 Measurement Locations

The field measurements were made during four periods spread over nine years. In 1987 data was collected for the pre-mine forest soils on the Hillslope Transect within the Del Park catchment. In 1989, 1990 and 1995 post-rehabilitation data was collected from the Hillslope Transect. In 1990 data was also collected from two areas not on the Hillslope Transect. These were Mine Area A within the Del Park catchment, and an area south of Mine Area C and just beyond the Del Park catchment divide. Table 2 lists the numbers and types of measurements made during each of the study periods. With regard to the site locations for the individual measurements, the * in the year column of Table 2 denotes where these are known accurately. For those unmarked, only the general area from which the measurements were made is known, though it appears

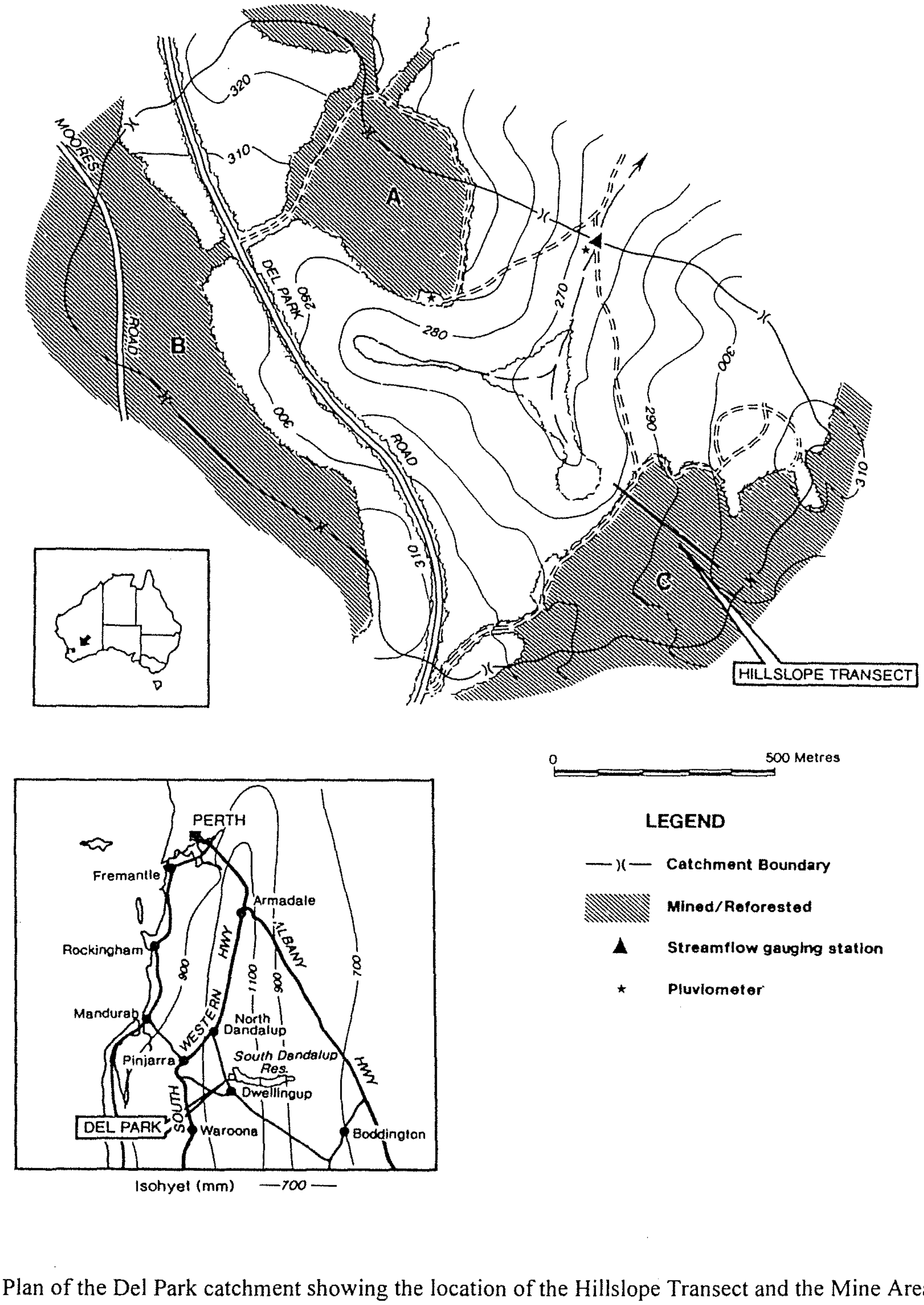

Figure 3: Plan of the Del Park catchment showing the location of the Hillslope Transect and the Mine Areas A, B & C.

likely that the measurements were made along a transect similar to the Hillslope Transect in Area C. Figure 4 shows the locations of the 1987 sites and Figure 5 shows the locations for the 1990 and 1995 sites. The ground surface contours plotted in Figure 5 are those after completion of mining and rehabilitation.

Table 2: Details of the measurements made during the four study periods. The * in the year column denotes whether the locations of the individual measurements are known.

Small Ring Infiltrometer

Year	No. of Reps.	Description of Item Measured with Short Title
1987 *	22	Hillslope Transect pre-mine native forest. (Pre-mine forest)
1987	6	Walking tracks in forest on Hillslope Transect. (Walk Tracks)
1989	16	Directly after minepit rehabilitation on Hillslope Transect. (1yr Rehab.)
1990 *	15	Second year after rehab. on Hillslope Transect. (2yr Rehab.)
1990	15	Fifth year after rehab. on area south of Area C. (5yr Rehab.)
1990	14	Thirteenth year after rehab. on Area A. (13yr Rehab.)
1995 *	15	Seventh year after rehab. on Hillslope Transect. (7yr Rehab.)

Well Permeameter

Year	No. of Reps.	Description of Item Measured with Short Title
1987 *	20	Hillslope Transect pre-mine native forest. (Pre-mine forest)
1989	16	Directly after minepit rehabilitation on Hillslope Transect. (1yr Rehab.)
1990 *	15	Second year after rehab. on Hillslope Transect. (2yr Rehab.)
1990	15	Fifth year after rehab. on area south of Area C. (5yr Rehab.)
1990	15	Thirteenth year after rehab. on Area A. (13yr Rehab.)
1995 *	15	Seventh year after rehab. on Hillslope Transect. (7yr Rehab.)

Disk Permeameter

Year	No. of Reps.	Description of Item Measured with Short Title
1995 *	14	Seventh year after rehab. on Hillslope Transect. (7yr Rehab.)

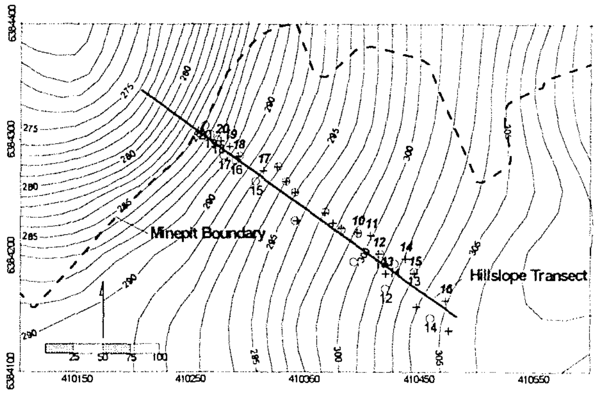

Figure 4: Location of measurement sites for 1987 pre-mining study. The ring infiltrometer sites are denoted by ✚ and well permeameter sites are denoted by O.

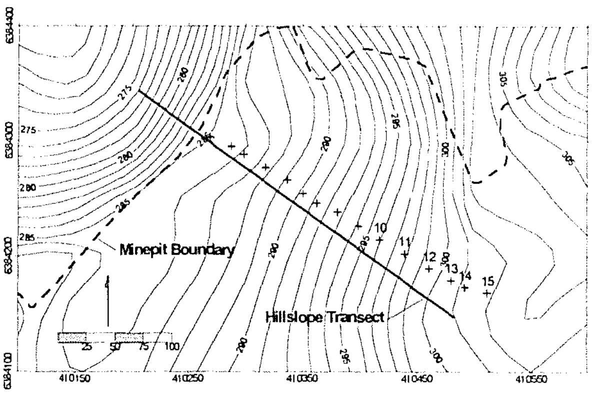

Figure 5: Location of measurement sites for 1990 and 1995 post-mining studies. Note that post-mining contours are shown.

3.2.2 Vegetation Cover

The original forest cover for the Hillslope Transect has been described by Ruprecht *et al.* (1987). The overstorey on the middle and upper slopes was dominated by jarrah (*Eucalyptus marginata*) and marri (*E. calophylla*) with bullich (*E. megacarpa)* on the lower slopes. Throughout the hillslope the middlestory was dominated by bull banksia *(Banksia grandis)* and sheoak *(Allocasuarina fraseriana)*. Basal area was estimated to be 29m^2/ha, projected crown cover was 45% and leaf area index (LAI) was estimated to be 1.4. Based on these measurements, the forest was categorised as medium density jarrah forest. The vegetation site type (Havel, 1975) was determined as P-S1 for the areas where the infiltration measurements where made.

Marshall (1996) reviewed the six year old vegetation cover on the rehabilitated section of the Hillslope Transect. He found that the dominant species were *Acacia celastrifolia, A. pulchella, Calothamnus spp., E. calophylla, E. marginata and Mirbelia dilatata.* From destructive sampling the LAI was estimated to be in the range 0.82 to 0.89. Marshall also undertook an extensive study of LAIs for ten plots with revegetation ages from three years to nine years. He found that LAI was highly variable from plot to plot. This makes it difficult, if not impossible, to estimate the likely vegetation covers for the infiltration measurement sites in different ages of revegetation. In general, it can probably be said that the LAI for the 1yr Rehab. sites would be practically zero, the LAI for the 2yr Rehab. 0.2 to 0.4, for the 5yr Rehab. 0.7 to 0.8, for the 7yr Rehab. 0.8 to 1.0 and for the 13yr Rehab. it is probably close to the original LAI or about 1.2 to 1.4.

3.2.3 Soil Profile Descriptions

All the 1987 pre-mining measurement sites had a defined duricrust layer. The depth to its top surface was measured for 19 of the well permeameter sites and gave an average of 490mm with a range from 250mm to 990mm. The above duricrust soils were brown piesolitic gravelly sands with a darker organically rich surface layer of about 100mm thickness. The duricrust varied from massive to unconsolidated and was typically about two metres thick (Ruprecht and Schofield - 1989).

The near surface soil profile for the post-mining measurement sites typically consisted of the original, above duricrust, soil spread to a depth of about 400mm across the mottled zone soils. Depending on the location, the mottled zone soils could be either in-situ or have been reworked during the pit landscaping phase. To promote water and plant root penetration, the profile is tilled to an average depth of 1.4m using a "winged" tyne.

4. Methods

4.1 Small Ring Infiltrometer

4.1.1 Basic principles

Ring infiltrometers are the simplest devices available for measuring soil surface infiltration capacity. A steel ring of known diameter is driven into the soil and water supplied from a graduated tank. The depth of water inside the ring is maintained at a constant level by a controlled feed from the tank. The level of water in the supply tank is recorded at regular intervals to allow calculation of the volume of infiltrated water as a function of time.

Water infiltrating from the ring will tend to diverge laterally as well a vertically and this is the major source of experimental error in the use of infiltration rings. The problem is lessened with the use of a large diameter ring and by keeping the depth of water in the ring to a minimum. Disturbance of the surface when the ring is driven into the soil is also a source of experimental error that can be minimised with the use of a large diameter ring.

4.1.2 Instrument design and operation

The small ring infiltrometers used at Del Park were 300mm in diameter and 200mm in height and made from stainless steel. In the 1987 experiments rings of 491mm and one metre diameter were also used. The rings were pushed into the soil to a depth of approximately 50mm. Where it wasn't possible to achieve this penetration a bentonite seal was placed around the outside of the ring. A water supply tank of 0.04 m^3 was positioned on the upslope side of the ring and the air inlet tube positioned so as to maintain a constant depth of between 10 and 40 mm in the ring.

4.1.3 Analysis of results

Theoretically, one dimensional, vertical infiltration into a deep, homogeneous soil of uniform initial water content is described by the Philip equation (Philip, 1957) for *I* the cumulative infiltration;

$$I = S t^{1/2} + A t \qquad (4.1)$$

with:

$$S = \int_{\theta_0}^{\theta_{sat}} \phi \, d\theta \qquad (4.2a)$$

$$A = \int_{\theta_0}^{\theta_{sat}} \chi \, d\theta + K_0 \qquad (4.2b)$$

where t is time; ϕ and χ are dependant on the $K(\theta)$ and $\psi(\theta)$ functions of the soil; S is the sorptivity which is the water content dependant absorption capacity of the soil in the absence of gravity effects; K is the hydraulic conductivity; θ is the volumetric water content; ψ is the soil water potential; and At reflects the gravity dependant infiltration capacity of the soil.

Equation 4.1 applies only to the period immediately after ponding occurs when capillarity is significant; at longer times the first term on the right hand side of Equation 4.1 approaches zero and $A \approx K_{sat}$. To cover both early and late times Equation 4.1 can be approximated by

$$I = S t^{1/2} + K_{sat} t \qquad (4.3)$$

The assumption of a deep, homogeneous soil profile is not valid at the Del Park catchment because of the occurrence of duricrust (see Section 3.2) at depths as shallow as 250mm. In addition, the topsoils at the catchment are so conductive that the sorptivity could not be determined for any of the experiments. In this case the saturated hydraulic conductivity is equal to the steady-state infiltration rate and this was determined by plotting infiltration rate as a function of time to check its stability and taking the average of the last four points.

4.2 Well Permeameter

4.2.1 Basic principles

Well permeameters are used to measure the saturated hydraulic conductivity of shallow sub-soils. The device consists of a water supply tank and a constant head device that can be lowered into a shallow, small diameter bore hole. As with the ring infiltrometer, the water level in the supply tank is measured at regular intervals to allow the calculation of the flow rate as a function of time.

4.2.2 Instrument design and operation

Bell and Schofield (1989) provide a full description of the permeameters used at Del Park and a detailed discussion of the possible sources of errors associated with their use. A water supply system was designed to deliver a flow rate of 1,000 mm/hr to ensure that measurement error in discharge rate remained below 5% for the highly pervious surface soils of the Del Park catchment. Water and air hoses of at least 20 mm external diameter were required, so the diameter of the borehole used in the experiments was a compromise between the need to comfortably fit both tubes into the hole and the need to keep the hole radius to a minimum to reduce the measurement time and volume of water required. A hole diameter of 45 mm was selected for all the experiments. Boreholes were nominally 500mm deep and the depth of water in the hole maintained at about 400 to 450mm. These specifications theoretically allow the well permeameter to measure saturated hydraulic conductivities up to 30m/day with minimal experimental error although conductivities greater than this were encountered during the field programme.

4.2.3 Analysis of results

Schofield (1987), and Bell and Schofield (1989) provide exhaustive discussions on the theoretical development of equations of flow from circular wells that include both the saturated and unsaturated flow components. If the unsaturated flow component is ignored the saturated hydraulic conductivity will be overestimated, the magnitude of the error being inversely proportional to the calculated value. They discuss the flow equations derived by Reynolds *et al.* (1983), Stephens *et al.* (1987) and Philip (1985) and concluded that Philip's (1985) solution was the most applicable for the Del Park experiments. Philip's equation is

$$\frac{K_{sat}}{Q_s} = \left(\gamma^2 - 1\right)^{-\frac{1}{2}} \left[\frac{4.117a^2\gamma\left(1-\gamma^{-2}\right)}{\ln\left\{\gamma + \left(\gamma^2 - 1\right)^{\frac{1}{2}}\right\} - \left(1-\gamma^{-2}\right)^{\frac{1}{2}}} + \frac{4.028a + 2.517a\gamma^{-1}}{0.5\alpha \ln\left\{\gamma + \left(\gamma^2-1\right)^{\frac{1}{2}}\right\}} \right]^{-1} \tag{4.4}$$

where K_{sat} is the saturated hydraulic conductivity; Q_s is the steady discharge rate from the well; $\gamma = H/a$; H is the constant head in the well; a is the radius of the well; and, α is the sorptivity derived from

$$K(\Phi) = K_{sat} \exp(\alpha\Phi) \qquad \alpha > 0,\ \Phi < 0 \tag{4.5}$$

where Φ is the pressure head of the soil.

There are two methods to determine the sorptive number, α. One involves performing two experiments using different constant heads and then solving for K_{sat} and α simultaneously using Equation 4.4; however, small experimental errors in the measurement of Q_s can result in $\alpha \rightarrow \pm\infty$ Alternatively, a laboratory experiment on an undisturbed core sample can be performed and Equation 4.5 solved for α; this method was considered beyond the scope of the experimental programme and would be extremely difficult given the gravelly nature of the top soils at Del Park.

Bell and Schofield reviewed the values of the sorptive number reported in the literature and found that for highly permeable soils α varies from 10 to 100m^{-1}. They recommend a constant value of α = 20m^{-1} for Darling Range soils to minimise errors in K_{sat}/Q_s. This approach was taken by Ruprecht and Schofield (1989) and was also adopted in this study.

4.3 Disk Permeameter

4.3.1 Basic principles

The disk permeameter is similar to the ring infiltrometer in that a stainless steel ring is driven into the soil to allow water to be ponded on the surface. However, a constant head is maintained by suspending a solid disk on which the water supply reservoir is mounted inside the ring. The water supply reservoir is sealed at the top and air enters through a small tube at its base. The head under which water infiltrates is equal to the vertical distance between the soil surface and the air inlet tube. By routing the air inlet tube through a bubble tower heads less than atmospheric pressure can be maintained, in which case the retaining ring is not required. However, negative pressure heads were not used in any of the Del Park disk permeameter experiments.

4.3.2 Instrument design and operation

The disk permeameters used at Del Park were of the type developed at the CSIRO Centre for Environmental Mechanics (CSIRO, 1988). The disk is 200 mm in diameter and is made from clear polycarbonate sheet. The water supply reservoir is also made from clear polycarbonate with the air inlet tube positioned 5 mm above the bottom of the disk. The holes at the bottom of the reservoir and beneath the air inlet tube are covered with fine stainless steel mesh (900 µm openings) to prevent, by surface tension, water from leaving the reservoir prior to the commencement of the experiment. Once water has been allowed into the space between the disk and the soil surface the mesh is coarse enough not to restrict the flow of water to the soil surface. The disk is suspended from the steel ring on three screws that adjust the height of the disk above the soil surface. Positive heads of between 5 and 10 mm were used in the Del Park experiments.

4.3.3 Analysis of results

For positive heads at the soil surface the hydraulic conductivity can be calculated from

$$K_{sat} = \frac{q}{\pi r^2} - \frac{4bS_0^2}{\pi r(\theta_0 - \theta_n)} \qquad (4.6)$$

where q is the volumetric flow rate; r is the radius of the disk; b is a dimensionless constant, set to 0.55 for most soils; S_0 is the sorptivity at the initial soil water content θ_n; and θ_0 is the soil water content at the supply potential, in this case θ_{sat}. However, to use Equation 4.6 it is necessary to measure the initial and saturated soil water contents, and also to determine the sorptivity. Due to the high hydraulic conductivity of the Del Park topsoils it was not possible to collect enough early time data to accurately calculate S_0. The saturated hydraulic conductivity was therefore determined from the steady-state infiltration rate in the same way as for the ring infiltrometer experiments.

5. Results and Analysis

5.1 Small Ring Infiltrometer

The Appendix lists the estimated K_{sat} values for each of the measurement sites and statistics summaries by measurement group. The group statistics have also been reproduced in Table 3. The statistics given are; mean, number of measurements, standard deviation, skewness coefficient, kurtosis with normal distribution as three and coefficient of variation as a percentage. Statistics have been given for the data in its original form, and when converted to geometric data by calculating the $\log_{10}$ for each measurement.

With regard to comparisons between measurement groups, Table 4 lists the two-tailed, unequal variance t-test statistics for all of the measurement groups. Results <0.10 are considered significant and have been shaded.

Table 3: Estimated K_{sat} values and statistics summaries for each group of small ring infiltration measurements for both normal data and $\log_{10}$ for each measurement.

	1987 Pre-mine		1987 Walk Track	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	21.2	1.24 (17.4)	12.9	1.00 (10.0)
N	22	22	6	6
Std Dev	13.9	0.28	9.2	0.35
Skewness	1.07	-0.02	0.69	-0.22
Kurtosis	0.21	-0.55	-0.99	-1.37
C of V %	66	23	72	35

Table 3 continued

	1989 1yr Rehab.		1990 2yr Rehab.	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	19.4	1.15 (14.2)	16.4	1.08 (12.1)
N	16	16	15	15
Std Dev	17.2	0.37	11.3	0.39
Skewness	1.95	-0.34	0.43	-0.59
Kurtosis	3.74	1.35	-0.65	-0.86
C of V %	89	32	69	36

Table 3 continued

	1990 5yr Rehab.		1990 13yr Rehab.	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	14.1	1.06 (11.6)	17.4	1.09 (12.3)
N	15	15	14	14
Std Dev	8.8	0.30	13.2	0.41
Skewness	1.31	-0.76	0.65	-0.52
Kurtosis	2.70	0.96	-0.77	-0.64
C of V %	62	29	76	38

Table 3 continued

	1995 7yr Rehab.	
	Arithmetic	Geometric
Mean	15.2	1.10 (12.5)
N	15	15
Std Dev	8.1	0.32
Skewness	0.53	-1.46
Kurtosis	0.37	2.24
C of V %	54	29

Table 4: Two-tailed, unequal variance t-test statistics for the small ring measurement groups for both normal data and $\log_{10}$ for each measurement. The significant results (<0.10) are shaded.

Statistics Arithmetic Values	1987 Walk Track	1989 1yr Rehab	1990 2yr Rehab	1990 5yr Rehab	1995 7yr Rehab	1990 13yr Rehab
1987 Pre-mine	0.11	0.74	0.26	0.06	0.11	0.41
1987 Walk Track	1	0.27	0.47	0.79	0.61	0.40
1989 1yr Rehab.		1	0.57	0.28	0.38	0.72
1990 2yr Rehab.			1	0.53	0.73	0.84
1990 5yr Rehab.				1	0.73	0.44
1995 7yr Rehab.					1	0.60
1990 13yr Rehab.						1

Table 4 Continued

Statistics Geometric Values	1987 Walk Track	1989 1yr Rehab	1990 2yr Rehab	1990 5yr Rehab	1995 7yr Rehab	1990 13yr Rehab
1987 Pre-mine	0.17	0.43	0.20	0.08	0.18	0.24
1987 Walk Track	1	0.40	0.65	0.72	0.58	0.64
1989 1yr Rehab.		1	0.62	0.47	0.66	0.66
1990 2yr Rehab.			1	0.87	0.92	0.98
1990 5yr Rehab.				1	0.76	0.85
1995 7yr Rehab.					1	0.95
1990 13yr Rehab.						1

The mean values given in Table 3 show that there has been a reduction, though not large, in K_{sat} for the rehabilitated minepit soils compared with the original forest. The mean value for the unmined forest using the geometric statistics, the geometric mean is normally used for hydraulic conductivities (Sharma, *et al.* - 1980), was 17.4m/day compared with values in the range 11.6 to 12.5m/day for the rehabilitated minepits. It should be noted that this is a large coefficient of variation considering that the data has been converted to $\log_{10}$ values, and that for the t-test results given in Table 4 only the 1990 5yr rehab. is considered significantly different from the pre-mining measurement group. The large coefficient of variations is explained in Figure 6.a, b and c where frequency distributions have been plotted for the small ring data. These distributions result from dividing the $\log_{10}$ values into the seven Z score classes of < -2.5, -2.5 to -1.5, -1.5 to -0.5, etc. to >2.5 and plotting these classes for the integer Z scores -3, -2, etc. All resultant distributions are wider than the normal distribution and therefore have a greater spread of data. The kurtosis values in Table 3 support this in that no value, except the arithmetic value for the 1989 1yr Rehab., exceeds the normal distribution value of three.

The low kurtosis values in Table 3 are caused by either; the distributions being platykurtic (flat in form) or bi-modal (two peaks to the distribution). The most extreme example of the platykurtic form is the Walking Track distribution, although care must be exercised in reaching conclusions about this frequency distribution as it is based on only six measurements. The Pre-mine and 1990 5yr Rehab. are much less marked in their platykurtic form. The most extreme form of the bi-modal distribution is shown by the 1990 2yr rehab. where the zero Z score (the mean) is located in a trough while two well defined peaks are at plus and minus one Z score. This implies that the data actually consists of two populations, one with a mean of 5m/day and the other with a mean of 30m/day, rather than a single population with the mean quoted in Table 3 of 12.1m/day. Given the uniformity of the topsoil, it is unlikely that the bi-modal form of the distributions is caused by differences in the topsoil material as such. It is more likely that it reflects a variation in the thickness of the topsoil over the mottled zone subsoil with the lower conductivity group having the thinner topsoil and thus the mottled zone sub-soil is acting as a limit to infiltration.

To better illustrate the variations between measurement groups the Z score on the x-axis of Figure 6 has been replaced by K_{sat}, giving the frequency distributions in Figure 7. The plotted K_{sat} values were derived by taking the geometric standard deviations given in Table 3 and plotting them about the geometric mean, using the Z scores -3 to 3 inclusive. Figure 7 shows that the major peak in each of the bi-modal distributions for the rehabilitated minepit measurement sets falls close to the original Pre-mine value. When a geometric mean is taken of the major peak values for the rehabilitated minepit measurements a value of 21.7m/day is obtained, slightly greater than the Pre-mine geometric mean of 17.4m/day.

The conclusion from the small ring infiltrometer experiments is that the conductivity of the sandy gravel topsoil layer is unchanged by mining and rehabilitation though there is evidence that infiltration rates are less, probably due to a lack of topsoil cover on some measurement sites allowing the mottled zone sub-soil to control the infiltration process. This will be discussed further in the next section.

Figure 6.a

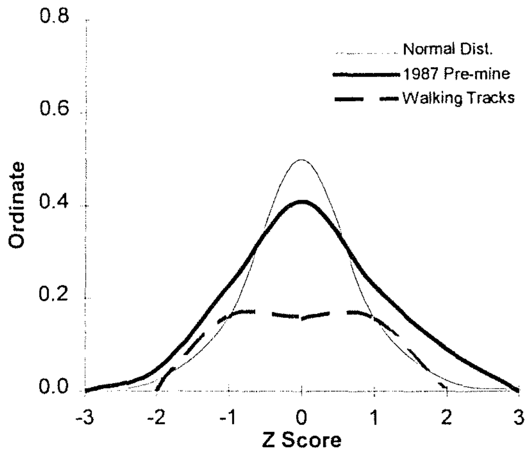

Figure 7.a

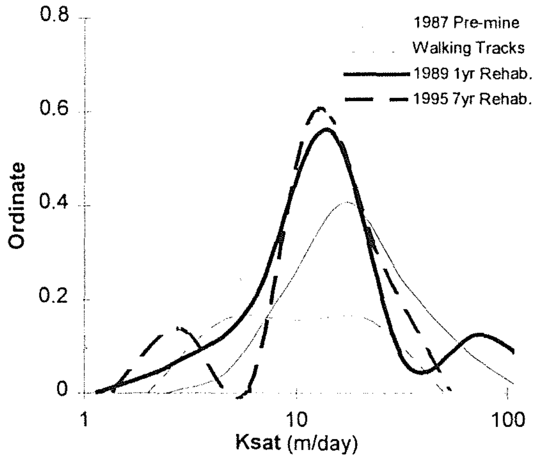

Figure 6.b

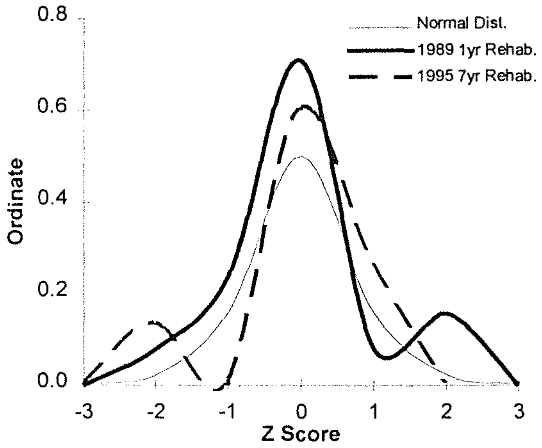

Figure 7.b

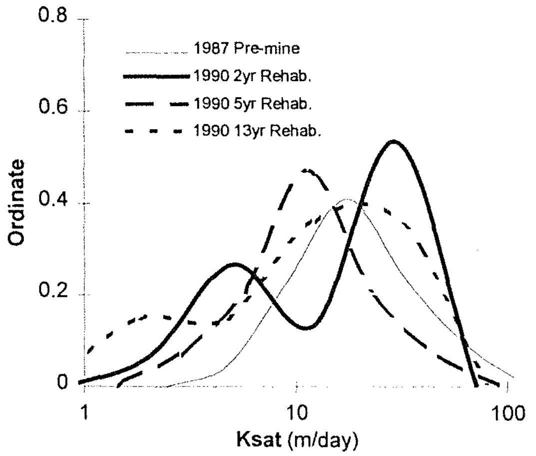

Figure 6.c

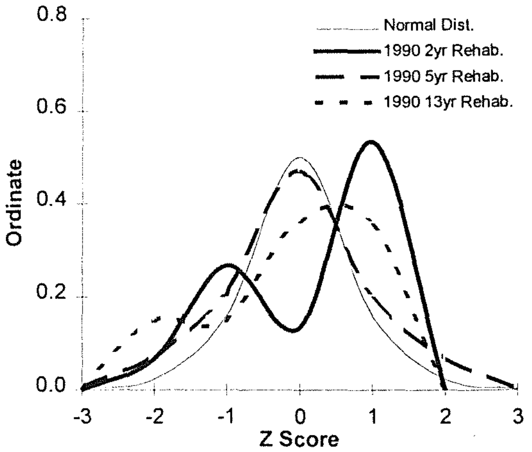

Figure 6: Frequency distributions for the small ring data.

Figure 7: Frequency distributions for the small ring infiltrometer data plotted with hydraulic conductivity instead of Z score along the x-axis.

5.2 Well Permeameter

The Appendix lists the estimated K_{sat} values for each of the measurement sites and statistics summaries by measurement group. The group statistics have also been reproduced in Table 5. The statistics given are; mean, number of measurements, standard deviation, skewness coefficient, kurtosis with normal distribution as three and coefficient of variation as a percentage.

With regard to comparisons between measurement groups, Table 6 lists the two-tailed, unequal variance t-test statistics for all the measurement groups. Results <0.10 are considered significant and have been shaded.

Table 5: Estimated K_{sat} values and statistics summaries for each group of well permeameter measurements for both normal data and $\log_{10}$ for each measurement.

	1987 Pre-mine		1987 Walking Tracks	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	13.1	1.04 (11.0)	2.38	0.08 (1.21)
N	20	20	16	16
Std Dev	7.5	0.27	2.7	0.56
Skewness	0.48	-0.14	1.20	-0.09
Kurtosis	-1.22	-1.25	-0.07	-0.87
C of V %	57	26	111	686

Table 5 continued

	1990 2yr Rehab.		1995 7yr Rehab.	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	1.88	0.068 (1.17)	2.17	0.196 (1.57)
N	15	15	15	15
Std Dev	2.1	0.43	1.6	0.40
Skewness	1.86	0.48	0.88	-0.74
Kurtosis	2.85	-0.29	-0.26	0.50
C of V %	113	624	75	204

Table 5 continued

	1990 5yr Rehab.		1990 13yr Rehab.	
	Arithmetic	Geometric	Arithmetic	Geometric
Mean	3.42	0.312 (2.05)	5.08	0.075 (1.19)
N	15	15	15	15
Std Dev	2.9	0.54	9.6	0.76
Skewness	0.80	-0.76	2.21	0.55
Kurtosis	0.11	-0.59	3.73	-0.25
C of V %	84	172	188	1013

The mean values of K_{sat} given in Table 5 clearly show a reduction in well permeability for the mined and rehabilitated sites compared with the pre-mining sites. The Pre-mine geometric mean was 11.0m/day compared with the range 1.17 to 2.05m/day for the rehabilitated measurement groups. This large difference is also reflected in the t-test statistics in Table 6; all the rehabilitated minepit measurement groups were significantly different from the Pre-mine values at the 0.01, or one percent, significance level.

Table 6: Two-tailed, unequal variance t-test statistics for the well permeameter groups for both the normal data and $\log_{10}$ for each measurement. The significant results are shaded.

Statistics Arithmetic Values	1989 1yr Rehab	1990 2yr Rehab	1990 5yr Rehab	1995 7yr Rehab	1990 13yr Rehab
1987 Pre-mine	0.00	0.00	0.00	0.00	0.01
1989 1yr Rehab.	1	0.56	0.30	0.78	0.31
1990 2yr Rehab.		1	0.11	0.68	0.23
1990 5yr Rehab.			1	0.15	0.53
1995 7yr Rehab.				1	0.26
1990 13yr Rehab.					1

Table 6 Continued

Statistics Geometric Values	1989 1yr Rehab	1990 2yr Rehab	1990 5yr Rehab	1995 7yr Rehab	1990 13yr Rehab
1987 Pre-mine	0.00	0.00	0.00	0.00	0.00
1989 1yr Rehab.	1	0.94	0.25	0.52	0.98
1990 2yr Rehab.		1	0.18	0.41	0.98
1990 5yr Rehab.			1	0.51	0.33
1995 7yr Rehab.				1	0.59
1990 13yr Rehab.					1

As for the frequency distributions for the measurement groups, the Pre-mine distribution is strongly bi-modal, see Figure 8, and the distributions for the rehabilitated minepit data are either bi-modal or skewed. As in the ring infiltrometer results, the well permeameter data seems to imply a splitting of the measurements into two populations, though for the rehabilitated minepit measurements the larger peak is now to the left of the graph whereas it was to the right for the ring infiltrometer measurements. From a study of the individual measurements which make up the lesser peak in these distributions, it appears likely that they are caused more by large voids or similar structures in the soils into which water can be rapidly lost rather than are a true reflection of the hydraulic properties of the soil matrix itself. The tillage of the sub-soil during rehabilitation to an average depth of 1.4m using a "winged" tyne would create a number of soft spots and large voids along the riplines; it is likely that a number of measurements were sited above or near such structures.

Figure 8.a

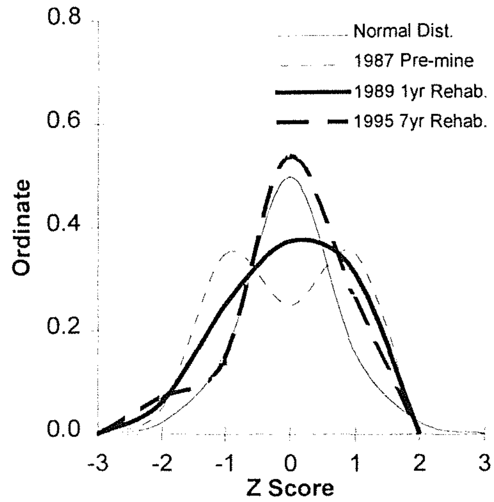

Figure 8.b

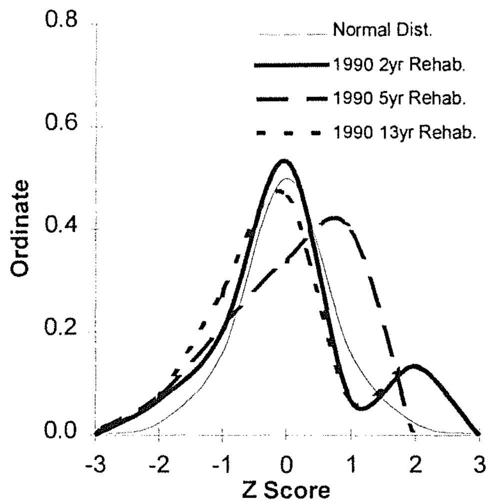

Figure 8: Frequency distributions for the measurement groups compared with a normal distribution.

Figure 9 shows the distributions for all the measurement groups plotted with K_{sat} instead of the Z score along the x-axis. These graphs allow a direct comparison between measurement group results. With regard to the bi-modal form of the Pre-mine distribution, it was found by simple regression that the distribution of K_{sat} wasn't related to either the depth to duricrust or distance up the hillslope. It appears likely that it is related to the presence and absence of large voids in the duricrust near the measurement site. If a large void were present K_{sat} would be higher than if it weren't; Ruprecht and Schofield (1989) determined that 15% of the area of the duricrust on the Hillslope Transect consisted of large voids.

Figure 9.a

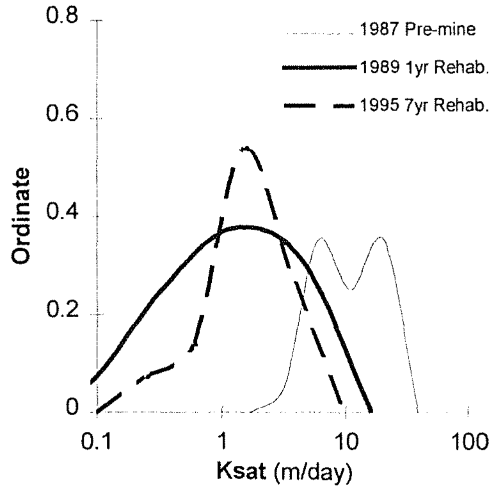

Figure 9.b

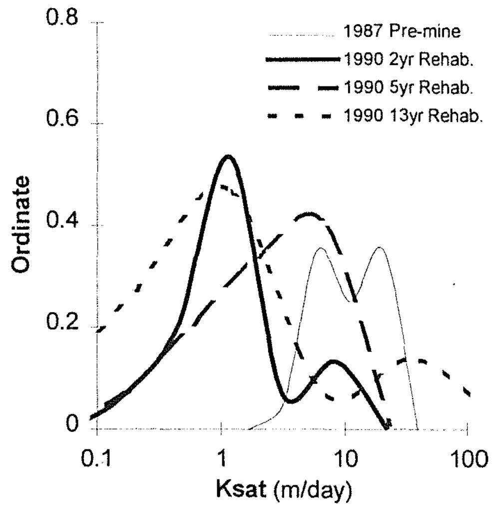

Figure 9: Frequency distributions for the well permeameter data plotted with hydraulic conductivity instead of Z score along the x-axis.

5.3 Disk Permeameter

A set of measurements were made in 1995 to test the effectiveness of a disk permeameter compared with the small ring infiltrometer. The Appendix lists the estimated K_{sat} values for each of the measurement sites and a statistics summary for the measurements. The statistics summary has also been reproduced in Table 7.

Table 7: Estimated K_{sat} values and statistics summary for the disk permeameter measurements made in 5yr Rehab. Statistics are given for both normal data and $\log_{10}$.

	Disk Permeameter	
	Arithmetic	**Geometric**
Mean	10.0	0.83 (6.8)
N	14	14
Std Dev	11.1	0.36
Skewness	2.89	0.88
Kurtosis	9.46	0.71
C of V %	110	43

Table 8: Two-tailed, unequal variance t-test statistics for the 7yr Rehab. disk permeameter, compared with 1987 Pre-mine and 7yr Rehab. for the ring infiltrometer groups for both normal and $\log_{10}$ for each measurement. The significant results (<0.10) are shown shaded.

Statistics for Arithmetic Values	Disk Permea.	1987 Pre-mine	1995 7yr Rehab.
Disk Permea.	1	0.01	0.16
1987 Pre-mine		1	0.11
1995 7yr Rehab.			1

Table 8 Continued

Statistics for Geometric Values	Disk Permea.	1987 Pre-mine	1995 7yr Rehab.
Disk Permea.	1	0.00	0.05
1987 Pre-mine		1	0.18
1995 7yr Rehab.			1

The geometric mean for the disk permeameter measurement group, which was in 7yr Rehab., was 6.8m/day compared with 12.5m/day for the 7yr Rehab. ring infiltrometer. Figure 10 is a plot of the frequency distributions for these two measurement sets with K_{sat} along the x-axis. It can be seen that both frequencies are bi-modal and have very similar form with the same K_{sat} values for the peaks. The only difference is that the ring infiltrometer has the higher peak to the right and the disk permeameter has the higher to the left. This interchange in higher peak position accounts for the difference in geometric means. The interchange is probably because the sample size is too small given the randomness in the data rather than from differences due to measurement method.

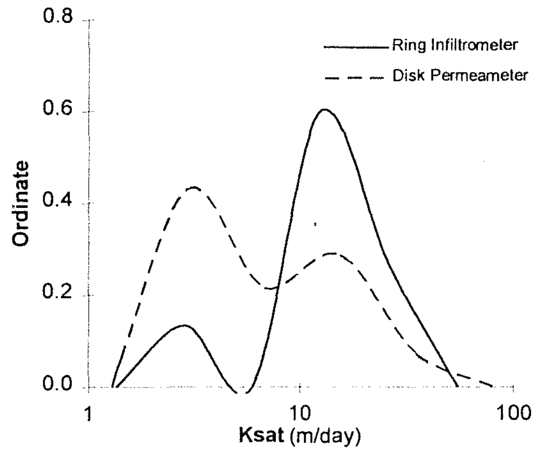

Figure 10: Frequency distribution for the 1995 disk permeameter data compared with the 1995 ring infiltrometer data.

6. Discussion

It was concluded from the ring infiltrometer measurements that the hydraulic properties of the topsoil hadn't been changed by collection and respeading during the mining and rehabilitation operations. The mean surface infiltration rate had been reduced but this was probably related to the thickness of topsoil rather than the topsoil properties. This finding is in variance from the observations of Huang, *et al.* (1996) who observed reductions in K_{sat} for forest soils in N.S.W. due to timber harvesting, Jorgensen and Gardner (1987) who observed an order of magnitude reduction in infiltration capacity due to mining in Pennsylvannia, USA and Sharma, *et al.* (1987) who found a reduction in soil surface infiltration capacity at Collie in the southern Darling Range due to clearing for pasture.

The work by Sharma, *et al.* is directly comparable with the present study as the surface soils are similar. They found that the arithmetic mean K_{sat} was 20.8m/day for the forested catchment compared with 3.1m/day for the cleared catchment converted to pasture. The arithmetic mean for forested, pre-mine measurements in the present study is 21.2m/day. The reasons for the K_{sat} of the rehabilitated mine pit to have remained at a similar level to the pre-disturbance forest, while the area converted to pasture hasn't, is probably related to the deep tillage process used in mine rehabilitation in combination with the lack of trafficking, both animal and machine, of the rehabilitated mine areas compared with the pasture. In particular, the development and use of a "winged" tyne for Alcoa's bauxite mine rehabilitation has resulted in a system an order of magnitude more efficient for deep tilling the soil than a conventional chisel tyne (Croton - 1985). The whole profile to a mean wing depth of 1.4m is lifted by the wing of the tyne and subjected to shear and displacement forces which completely break-up any compaction and cementation. The study sites of Huang, *et al.* and Jorgensen and Gardner were not subjected to such a tillage process.

The measurements made using the well permeameter showed a reduction in permeability at depth from 11m/day for the pre-mine case to 1 to 2m/day for the rehabilitated minepit cases. While this reduction in permeability is large, it isn't sufficient to explain the observations by Croton and Tierney (1985) of water ponded in mine areas after rainfalls of 100mm or less. Five additional measurements were made in 1989 with the well permeameter, using holes augered deeper into the mottled zone of the tillage layer to eliminate any possibility of conductivities being artificially raised by part of the water filled section of the hole being in the topsoil. These gave a geometric mean K_{sat} of 1.37m/day which is consistent with the means for the other rehabilitated minepit measurements and implies that these measurements are realistic.

The reason for ponding in rehabilitated minepits during rainfalls of 100mm or less is probably due to the reduction in hydraulic conductivity once the base of the tillage zone is reached. Croton and Tierney (1985) defined a relationship between depth of mined bauxite and infiltration rate beyond the tillage layer. This relationship varied from 45mm/day for a depth of zero to 100mm/day for a minable ore depth of 5.5m. For the Hillslope Transect it would be about 70mm/day. Raper and Croton (1996) reviewed all available data for K_{sat} for the mottled zone and determined a geometric mean of 52mm/day. This value is consistent with the range used by Croton and Tierney.

It is therefore highly likely that while the infiltration measurements reviewed in this report have improved our understanding of the hydraulic properties of near-surface rehabilitated minepit soils, they haven't defined the infiltration capacity of the control for runoff generation in rehabilitated minepits, which is probably the conductivity of the mottled zone directly below the tillage layer. For this reason, the direct use of the above infiltration data in the definition of runoff from a PMP type event could result in an erroneous result. The data would, however, be useful in the definition of a layered, deterministic model of the system which included the mottled zone beneath the tillage layer. Such modelling would fulfil the objectives of the study in that it would both aid PMF estimation and the hydrological studies of the JIRZRP.

7. Conclusion

The conclusions of the study were that the hydraulic conductivity of the above duricrust topsoil layer was not significantly altered by bauxite mining and rehabilitation although the soil surface infiltration capacity was decreased. This decrease appeared to be related to the properties of the mottled zone within the tillage layer and its proximity to the surface, rather than the properties of the topsoil layer. It was found that permeabilities at depth were considerably less for the rehabilitated minepits compared with the native forest. The geometric mean for K_{sat} for the pre-mine case was 11m/day compared with 1 to 2m/day for the rehabilitated minepit cases. This difference was considered to be related to the conductivity of the mottled zone tillage layer compared with the conductivity of the vertical holes through the duricrust.

It was concluded from a review of other published hydraulic conductivity data for the mottled zone that the primary control for infiltration in rehabilitated minepits at rainfalls near to the PMP would be the conductivity of the mottled zone directly beneath the tillage zone. The conductivity of this layer would probably be in the range 45 to 100mm/day or 170 to 300 times less than the conductivity of the soil surface.

With regard to the data itself, it was found that virtually all of the measurement groups had frequency distributions displaying either a skew or a bi-modal form. These resulted in mean values which were often unrealistic or could be radically changed by the deletion of one or two values. The method of converting the data into frequency distributions with hydraulic conductivity along the x-axis was essential in interpreting the data. The comparison between small ring infiltrometer and disk permeameter was a case in point, where the disk permeameter had a geometric mean half that of the ring infiltrometer but the bi-modal form of the two distributions implied that this difference was related to randomness within the data rather than to any real difference in measurement method.

8. Recommendations

While the study failed to define the likely infiltration rates for a rehabilitated minepit during a PMP event, it did highlight that the likely limit to infiltration under these conditions would probably be conductivity of the mottled zone beneath the tillage layer. It was concluded that if additional data were collected for this layer and used in a layered deterministic model of the system estimates could be made of infiltration under PMP conditions. To achieve this, the following recommendations are made.

1. Undertake a well permeameter study of the hydraulic properties of the mottled zone directly beneath the tillage zone. This study could be simplified by undertaking it in holes dug in mine areas prior to rehabilitation.
2. Employ the results of the mottled zone properties study, in combination with other infiltration and soil properties data, in a layered, deterministic model of the rehabilitated minepit soil profile. An example of a model that could be used is WEC-C (Croton - 1995).

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Appendix - Estimated K_{sat} Values and Statistics

Small Ring Infiltrometer and Disk Permeameter

	1987 Pre-mine	
Site	**Normal**	**Log**
1	7.7	0.89
2	13.6	1.13
3	16.3	1.21
4	21.4	1.33
5	9.2	0.96
6	37.7	1.58
7	6.5	0.81
8	40.0	1.60
9	13.6	1.13
10	38.1	1.58
11	19.5	1.29
12	48.4	1.68
13	24.3	1.39
14	10.7	1.03
15	4.7	0.67
16	10.7	1.03
17	16.9	1.23
18	19.3	1.29
19	26.5	1.42
20	54.0	1.73
21	12.6	1.10
22	15.4	1.19
Mean	**21.2**	**1.24 (17.4)**
N	22	
Std Dev	13.9	0.28
Skewness	1.07	-0.02
Kurtosis	0.21	-0.55
C of V %	66	23

	1987 Walking Tracks	
Site	**Normal**	**Log**
Track 1	20.9	1.32
Track 2	11.9	1.08
Track 3	3.3	0.52
Track 4	4.9	0.69
Track 5	26.9	1.43
Track 6	9.4	0.97
Mean	**12.9**	**1.00 (10.0)**
N	6	
Std Dev	9.2	0.35
Skewness	0.69	-0.22
Kurtosis	-0.99	-1.37
C of V %	72	35

1989 1yr Rehab.

Site	Normal	Log
1	10.8	1.04
2	20.5	1.31
3	6.3	0.80
4	50.7	1.70
5	8.8	0.94
6	11.8	1.07
7	21.3	1.33
8	20.4	1.31
9	6.8	0.83
10	16.2	1.21
11	10.4	1.02
12	12.9	1.11
13	15.0	1.18
14	1.9	0.28
15	67.8	1.83
16	29.5	1.47
Mean	**19.4**	**1.15 (14.2)**
N	16	
Std Dev	17.2	0.37
Skewness	1.95	-0.34
Kurtosis	3.74	1.35
C of V %	89	32

1990 2yr Rehab.

Site	Normal	Log
1	20.7	1.32
2	38.9	1.59
3	4.2	0.62
4	2.1	0.32
5	4.5	0.65
6	4.6	0.67
7	24.4	1.39
8	9.5	0.98
9	19.0	1.28
10	6.2	0.79
11	22.8	1.36
12	33.2	1.52
13	12.8	1.11
14	22.3	1.35
15	21.5	1.33
Mean	**16.4**	**1.08 (12.1)**
N	15	
Std Dev	11.3	0.39
Skewness	0.43	-0.59
Kurtosis	-0.65	-0.86
C of V %	69	36

1995 7yr Rehab.

Site	Normal	Log
1	2.1	0.32
2	11.4	1.06
3	11.4	1.06
4	24.1	1.38
5	12.3	1.09
6	13.6	1.13
7	2.9	0.46
8	12.3	1.09
9	31.4	1.50
10	15.1	1.18
11	19.2	1.28
12	15.4	1.19
13	12.6	1.10
14	29.1	1.46
15	14.9	1.17
Mean	**15.2**	**1.10 (12.5)**
N	15	
Std Dev	8.1	0.32
Skewness	0.53	-1.46
Kurtosis	0.37	2.24
C of V %	54	29

1990 5yr Rehab.

Site	Normal	Log
1	11.6	1.06
2	4.3	0.63
3	14.0	1.15
4	13.9	1.14
5	22.1	1.34
6	37.5	1.57
7	5.8	0.77
8	11.3	1.05
9	13.0	1.11
10	19.3	1.29
11	13.9	1.14
12	22.5	1.35
13	11.9	1.08
14	7.7	0.88
15	2.3	0.36
Mean	**14.1**	**1.06 (11.6)**
N	15	
Std Dev	8.8	0.30
Skewness	1.31	-0.76
Kurtosis	2.70	0.96
C of V %	62	29

	1990 13yr Rehab.	
Site	**Normal**	**Log**
1	43.4	1.64
2	17.4	1.24
3	10.9	1.04
4	27.8	1.44
5	9.2	0.96
6	2.0	0.30
7		
8	15.4	1.19
9	5.0	0.70
10	35.1	1.54
11	26.0	1.42
12	10.0	1.00
13	2.9	0.46
14	6.4	0.80
15	31.9	1.50
Mean	**17.4**	**1.09 (12.3)**
N	14	
Std Dev	13.2	0.41
Skewness	0.65	-0.52
Kurtosis	-0.77	-0.64
C of V %	76	38

	Disk Permeameter 7yr	
Site	**Normal**	**Log**
1	3.0	0.48
2	10.5	1.02
3	7.3	0.86
4	4.1	0.62
5	3.6	0.56
6	2.3	0.35
7	11.4	
8	4.6	0.67
9	9.4	0.97
10	18.5	1.27
11	10.6	1.02
12	11.0	1.04
13	46.6	1.67
14	3.2	0.51
15	4.3	0.64
Mean	**10.0**	**0.83 (6.8)**
N	14	
Std Dev	11.1	0.36
Skewness	2.89	0.88
Kurtosis	9.46	0.71
C of V %	110	43

Well Permeameter

	1987 Pre-mine	
Site	Normal	Log
PRM1	14.8	1.17
PRM2	23.2	1.36
PRM3	18.1	1.26
PRM4	5.1	0.71
PRM5	7.1	0.85
PRM6	10.9	1.04
PRM7	5.5	0.74
PRM8	13.8	1.14
PRM9	3.5	0.55
PRM10	6.2	0.79
PRM11	11.9	1.08
PRM12	5.0	0.70
PRM13	23.9	1.38
PRM14	8.0	0.90
PRM15	22.6	1.35
PRM16	16.4	1.22
PRM17	7.2	0.86
PRM18	22.3	1.35
PRM19	8.9	0.95
PRM20	26.7	1.43
Mean	**13.1**	**1.04 (10.99)**
N	20	
Std Dev	7.5	0.27
Skewness	0.48	-0.14
Kurtosis	-1.22	-1.25
C of V %	57	26

	1989 1yr Rehab.	
Site	Normal	Log
1	0.30	-0.53
2	1.44	0.16
3	5.43	0.74
4	0.55	-0.26
5	1.95	0.29
6	0.81	-0.09
7	1.90	0.28
8	2.37	0.37
9	0.64	-0.19
10	5.92	0.77
11	0.42	-0.38
12	0.96	-0.02
13	0.23	-0.63
14	0.11	-0.96
15	7.27	0.86
16	7.85	0.89
Mean	**2.4**	**0.083 (1.21)**
N	16	
Std Dev	2.7	0.56
Skewness	1.20	-0.09
Kurtosis	-0.07	-0.87
C of V %	111	686

1990 2yr Rehab.		
Site	Normal	Log
1	0.67	-0.17
2	0.47	-0.33
3	1.64	0.21
4	0.39	-0.41
5	7.55	0.88
6	0.72	-0.14
7	5.14	0.71
8	1.20	0.08
9	0.95	-0.02
10	0.76	-0.12
11	1.86	0.27
12	1.53	0.19
13	0.75	-0.13
14	0.23	-0.63
15	4.36	0.64
16	**1.9**	**0.068 (1.17)**
N	15	
Std Dev	2.1	0.43
Skewness	1.86	0.48
Kurtosis	2.85	-0.29
C of V %	113	624

1995 7yr Rehab.		
Site	Normal	Log
1	0.42	-0.37
2	1.41	0.15
3	4.22	0.63
4	5.60	0.75
5	3.98	0.60
6	1.52	0.18
7	1.30	0.11
8	2.12	0.33
9	1.34	0.13
10	1.82	0.26
11	1.13	0.05
12	4.36	0.64
13	0.63	-0.20
14	0.20	-0.71
15	2.43	0.39
Mean	**2.2**	**0.20 (1.57)**
N	15	
Std Dev	1.6	0.40
Skewness	0.88	-0.74
Kurtosis	-0.26	0.50
C of V %	75	204

1990 5yr Rehab.		
Site	Normal	Log
1	1.38	0.14
2	0.55	-0.26
3	2.09	0.32
4	6.43	0.81
5	3.08	0.49
6	5.00	0.70
7	7.10	0.85
8	0.45	-0.35
9	2.73	0.44
10	4.59	0.66
11	4.97	0.70
12	9.86	0.99
13	0.18	-0.75
14	0.33	-0.48
15	2.62	0.42
Mean	**3.4**	**0.31 (2.05)**
N	15	
Std Dev	2.9	0.54
Skewness	0.80	-0.76
Kurtosis	0.11	-0.59
C of V %	84	172

1990 13yr Rehab.		
Site	Normal	Log
1	0.39	-0.41
2	2.10	0.32
3	25.87	1.41
4	1.65	0.22
5	9.35	0.97
6	0.65	-0.19
7	0.42	-0.38
8	29.96	1.48
9	0.72	-0.14
10	1.32	0.12
11	2.55	0.41
12	0.08	-1.08
13	0.81	-0.09
14	0.22	-0.66
15	0.14	-0.85
Mean	**5.1**	**0.076 (1.19)**
N	15	
Std Dev	9.6	0.76
Skewness	2.21	0.55
Kurtosis	3.73	-0.25
C of V %	188	1013