THE INFLUENCE OF VEGETATION ON LEACHATE GENERATION FROM SOLID WASTE PILES PRODUCED BY MINING PROJECTS: THE RUNDLE EXAMPLE.

by

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PREFACE

Prior to embarking on a course of study leading to the Master of Environmental Studies degree I was employed by Esso Australia Ltd. (Esso) as an Environmental Engineer assigned to the Rundle project. One of the tasks that I undertook in this role was the establishment of the Rundle waste dump leachate program. I was involved in the project definition, construction and installation of the field research station, and with the ongoing modelling by the University of Queensland. As a result of my work with them Esso very kindly offered to make available, for the purposes of this thesis, information collected by the waste dump leachate program. Planning for this thesis commenced in July 1986. One objective was to fulfill the need of the Rundle waste dump leachate program for an investigation into the influence of vegetation on water movement and leachate generation. This had been identified as an area in need of work for some time prior to the start of this project.

I have had an ongoing contact with the leachate program in the role of consultant to the project. Esso have also supported four site visits to Rundle to collect data for this thesis.

A number of field studies are described in Chapter 4 of this thesis. Some studies were carried out by me especially for this thesis, other studies were carried out for the overall leachate program by myself or other workers.

The soil moisture determinations described in Section 4.1 were carried out by a local contractor. The measurements taken in the lysimeters were for the overall program. The other soil moisture determinations taken in study plots 3 to 7 were made specifically for this thesis. I determined the location of the access tubes, installed some of them (with considerable help from Esso and the local contractor) and defined the measuring program.

The lysimeter study (Section 4.2), was the key element in the waste dump leachate program. I was extensively involved with this program in my role as Environmental Engineer for Esso and very fortunate that I was able to use the information gained from the lysimeters in this thesis.

The runoff determinations (Section 4.3) were originally initiated by me as part of the leachate program with a view to incorporating the results into an assessment of water movement in the vegetated layers. Thus the information obtained from this study was not used until I commenced this thesis.

The meteorological data (Section 4.4) comprises a central element of the Rundle waste dump leachate program. One of my responsibilities, both as employee and as consultant to Esso has been the calibration and analysis of the Rundle meteorological data.

Most of the information regarding material characteristics (Section 4.5) was obtained from earlier rehabilitation studies. The detailed chemical analysis was carried out for the leachate program.

I obtained Leaf Area Index information (Section 4.6) and carried out the vegetation survey (Section 4.7) to obtain data for the thesis. The four site visits which Esso very generously supported were primarily for collection of the Leaf Area Index information and to carry out a vegetation survey.

ACKNOWLEDGMENTS

1. I would like to thank the Rundle Project Group and Esso Australia Ltd. for making available the data and equipment that was utilised in this thesis, for providing financial support, and the opportunity to make four site visits to Rundle for the purposes of data collection. In particular I would like to thank Mr. Barry Thompson for his ongoing assistance, support, encouragement and interest. I would like to thank Mr. Russell Tait for his guidance during this project, particularly his constructive comments during the formulation of the initial ideas for the thesis.

2. I would like to acknowledge the support of the Commonwealth Government, Department of Education, Employment and Training by the provision of a Commonwealth postgraduate course award.

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ABSTRACT

Many large scale mining projects produce large waste piles of low grade ore, overburden and processing waste. Without appropriate planning and management there is a potential for rain soaking through the waste piles, to wash small quantities of chemicals out of the piles. One method that has been suggested for reducing the quantity of rain soaking into the piles is to vegetate the surface of the waste piles to use evapotranspiration to reduce the volume of water available for leachate generation. Little research has been done to quantify the effectiveness of this technique. Similarly extensive research into plant, water soil interactions has not been applied to mining projects.

Commercial oil production from the Rundle Oil Shale resource (located near Gladstone, Queensland) will produce large quantities of solid wastes. In association with the Chemical Engineering Department at the University of Queensland the Rundle Joint Venture is undertaking a research program to develop and verify a computer model of the transport of leachate in the waste dumps. As part of this program this thesis develops a computer model of the water flows in the surface of the waste dumps. The model is a water balance model; it was calibrated using field data collected from Rundle site. Additional field data were used to verify the predictions made by the calibrated model. Measured and predicted values generally agreed within 10%.

The model was run using average data collected over a long period to make predictions of the frequency and quantity of water draining downwards beyond the root zone that would have the potential for leachate generation. A relationship between age of vegetation and frequency of drainage was established. The effect of climate change (increase and decrease of rainfall or evaporation) on the frequency of drainage beyond the root zone was investigated and a relationship established.

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1. INTRODUCTION

1.1 Solid Waste Disposal from Mining

Mining, both underground and open cut, produces quantities of solid waste material which must be disposed of. This material includes overburden (material overlying the deposit), low grade ore unsuitable for processing and the wastes from the processing. There are a number of options for the disposal of the solid wastes:

(a) Place the material in piles on the surface at a convenient location near the mine.

(b) Refill the voids created by the removal of material by mining.

(c) Store the tailings (residue from the processing of ore, often a slurry) in dams and leave to evaporate or drain.

(d) Solid wastes can be dumped directly into a river, lake or ocean.

The first three of these methods are widely used, both today and in the past. The last method, fairly widespread in the past, is less common today. The scope of this thesis is limited to the first of these options, although for operational and space reasons some surface dumping takes place when refill of mining voids is the primary disposal method.

In the past, the solid waste material was dumped in the most convenient manner with no attention to environmental, health, safety and land use implications. Material was abandoned with no further treatment or management (Bradshaw and Chadwick 1980, and Gilpin 1981). There is a widespread legacy of this philosophy for handling waste materials throughout the world, for example, Bradshaw and Chadwick (1980) quoted a 1971 estimate that 0.4% (approximately 980 square kilometers) of the total land area in Great Britain could be classified as derelict as a result of mining and industrial activities. In Australia the proportion of derelict land resulting from mining activities is much less. Less than 0.02% of Australia's land area is occupied by mining, however this still accounts for over 1500 square kilometres (Brooks 1987). Unplanned and uncontrolled dumping of solid waste material has continued until recently at many sites such as Rum Jungle, operational from 1952 to 1971 (Department of Mines and Energy, Northern Territory undated), Captains Flat, operational from 1874 until 1962 (Craze 1979) and Mt. Lyell operational from 1884 (Blainey 1954).

Four major forms of environmental degradation can result from this type of solid waste disposal:

(a) Visual, landscape degradation.
(b) Land degradation resulting from the removal of a resource for multiple use.
(c) Dust and particulate loading in the air.
(d) Reduction in the quality of surface water and ground water in the surrounding region.

Once the disposal site is established these types of degradation can be controlled. The visual and land degradation aspects can be eliminated or significantly reduced by a planned rehabilitation program. Dust generation can be controlled by surface treatment or revegetation. Deterioration of water quality arises, generally, from either runoff and erosion, leachate generation or a combination of both. Treatment, once a problem is identified is not as straight forward as treatment of the other forms of degradation. As discussed in Section 1.3 this thesis focuses on aspects of leachate generation, potential consequences, prediction and prevention.

Since the 1960s the mining industry has been paying more attention to environmental aspects of its activities. This has arisen partially because of changes to mining legislation and the introduction of legislation for the protection of the environment and partially because of the change in public attitude which demands a greater level of public protection (Craze 1981, Brooks 1987). For example, in States such as Tasmania the Environment Protection legislation overrides the requirements of the mining legislation. Where political pressure is strong, for example, waste piles from profitable operating mines near populated areas, many companies have undertaken rehabilitation programs although they were not legally obliged to do so (Trevis 1980, Craze 1981).

There are cases where pollution and degradation exist in an area as a result of earlier mining activities. These mines are now closed and, in most cases, the company that operated the mine no longer exists. In particular cases the Commonwealth Government has provided funds to the State or Territory to undertake major rehabilitation works. Rum Jungle in the Northern Territory and Captains Flat in New South Wales are two examples of the use of Commonwealth funds for rehabilitation purposes (Craze 1979, Willis 1984). No rehabilitation usually takes place if Commonwealth funds are not available.

More recently, in the 1980s, companies seeking to establish new mines have attempted to identify potential environmental problems before they occur. This enables selection and implementation of solutions before problems arise. This is achieved by a system of integrated project planning including economic, technical, environmental, and geological elements. It has been identified as the most efficient method of planning a new mining operation for a company seeking permission to establish a new mine. The environmental impact statement produced for Olympic Dam uranium project (Kinhill Stearns Roger Joint Venture, 1982) illustrates the results of this integrated planning system. Integrated planning becomes more important as technological changes enable a much larger scale of operations than was possible even 20 years ago. Tait and Cutler (1987) describe a more specific example, the interrelationship between mine planning and environmental assessment for the solid waste disposal aspects of the Rundle Oil Shale Project.

Integrated planning approaches seek to predict potential environmental effects before they occur and prescribe preventative or mitigation measures.

1.2 Leachate Generation from Solid Waste Piles

Leachate occurs when liquid, usually rain, percolates through a pile of solid material removing, in the liquid phase, any mobile chemical or organic components. The process is known as leaching and the liquid moving through the solid material as leachate. Two aspects of leachate generation are important: the flow and the composition of the leachate. These depend on a variety of factors such as the nature of the solid and liquid, temperature, availability of oxygen, microbial action, and evaporation.

The quality of the leachate can vary from containing components at similar levels to the waters in the undisturbed environment in a particular area to being extremely toxic. The quality of leachates tends to be low if iron pyrites is present in the solid material. An acid leachate may be produced which mobilises trace heavy metals which are otherwise not leached out. Even when iron pyrites is not present the nature of the material, for example, the organic content, may result in a leachate with the potential to degrade the surrounding environment.

The impact of leachate generation on the water quality downstream of the waste pile is often exacerbated by erosion and runoff containing a significant particulate load as well as a chemical load. This occurs with poor or no surface water management and low surface stability.

Leachates, if they occur, may move into the groundwater or the surface water system near a waste pile.

The literature review in Chapter 2 includes a review of the treatment options that are available to neutralise the effects of leachates, or to stop their flow. Historically, mining companies did not consider the effects of their operations, including leachate generation, on the environment. More recently, when leachate problems were identified, attempts were made to implement remedial measures. Very recently pre-mining planning has predicted the possible quantity and quality of leachates before their occurrence. If leachate is predicted to be a potential problem the next step is to design the solid waste pile so as to minimise leachate generation and design a collection or treatment system.

Techniques which can be incorporated into the dump design to eliminate or minimise leachate generation include minimising infiltration by maximising runoff (without erosion), maximising evaporation from the dump surface by suitable revegetation (that is maximising evapotranspiration) and provision of a seal layer over the dump.

1.3 Effects of Revegetation on Leachate Generation

Revegetation is an important element in the design of any solid waste dump. The dump surface can be stabilised, erosion reduced, evaporation increased, dust reduced and the appearance improved by an effective revegetation strategy. This thesis relates revegetation to its effect on leachate generation, and develops a computer model to predict the quantity of water available for leachate generation for a particular example: The Rundle Oil Shale Project.

Two hypotheses are put forward in the thesis:

(a) Revegetation of a mining waste dump reduces the water available for leachate generation within the dump. Water falling on a waste dump as rain is usually transported through the dump, possibly adsorbing chemical compounds, and can then be released into the local surface or groundwater system. Revegetation results in water uptake by plants through the process of evapotranspiration, and hence a reduction in the quantity of water available for leachate generation.

(b) <u>For a given example (i.e., revegetation trial plots for the Rundle Oil Shale Project) water infiltration beyond a boundary layer can be predicted as a function of season, rainfall events and age of vegetation.</u> The quantity of water removed by evapotranspiration is related to a number of factors such as climate, vegetation type, and age of vegetation. Predictions of evapotranspiration can be tested by measurement. Knowledge of evapotranspiration and rainfall will give, by mass balance, a measure of the quantity of water moving beyond the root zone of the vegetation, and hence becoming available for leachate generation.

In order to argue these hypotheses, literature is reviewed in three areas:

(a) Leachate generation from solid waste piles resulting from mining activities.

(b) The research into disposal of the solid wastes generated by the Rundle Oil Shale Project.

(c) Soil-vegetation-water interaction.

The information from the literature search (Chapter 2) is used to develop a research plan (Chapter 3). The research plan involves two distinct elements, the development of a computer model of evapotranspiration for revegetation on the Rundle waste dumps (Chapter 3) and the collection of field data over a period of 2.5 years (Chapter 4). The data collected in the field studies is used to verify the computer model. These results are discussed (Chapter 5) in order to develop conclusions and recommendations (Chapter 6).

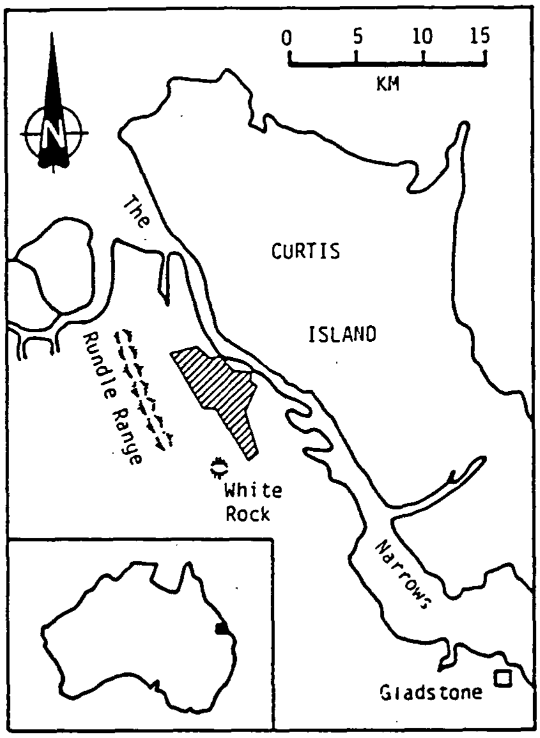
1.4 The Rundle Example

The Rundle Oil Shale Project is a joint venture between Esso Exploration and Production Australia Inc. (50% and operating interest), Southern Pacific Petroleum N.L. (25% interest) and Central Pacific Minerals N.L. (25% interest).

A brief description of the project follows (Cutler 1988). The Rundle Oil Shale deposit occurs on the central Queensland coast, about 27 kilometres northwest of Gladstone. The terrain at Rundle is flat to gently undulating rising to hills immediately west of the deposit. To the east of the deposit is the shallow tidal Narrows Channel. The eucalypt forest of the region varies from open to medium cover, with mangroves along the tidal inlets. Munduran Creek is the major drainage system in the project site and flows in a north easterly direction across the proposed mine area. Figure 1.1 shows a sketch of the area. The oil shale deposit occurs in a major down faulted block which has protected the sediments from subsequent erosion. The oil shales are of tertiary age overlain by between 10 metres and 30 metres of overburden. The Tertiary sediments are in three formations: the Curlew Formation, the Rundle Formation and the Worthington Formation. The Rundle Formation contains the major oil shale seams. The other two formations, refered to as interburden, are dominantly claystones with minor carbonaceous shales, sandstones, conglomerates and limestones.

The probable geological ore resource for the Rundle Deposit is estimated to be 5,000 million tonnes of oil shale at an average grade of 105 litres per tonne. The cutoff criteria for this estimate is 50 litres per tonne.

A series of evaluations since 1979 have considered a range of development options for the Rundle deposit. Older



▨ - Rundle Project Area

FIGURE 1.1 Location of the Rundle Project references to the Rundle project often refer to earlier, larger scale development and not the present planning basis. Even some recent papers, such as Considine (1987), refer to the early planning basis. The current development planning basis arose largely from the Rundle Commercialisation Study (RCS) completed in September 1984 (Moore and Thompson 1984). The objective of the study was to "evaluate a commercial Australian oil shale project that employs low cost design/construction concepts."

The planning basis provides for a three stage development, each stage commencing eight years apart, with a minimum project lifetime of thirty years. The total capacity will be 125,000 tonnes per day of as mined shale feed. Stage 1 will process 25,000 tonnes per day of Kerosene Creek (KC) shale. Stages 2 and 3 will each process 50,000 tonnes per day of Munduran Creek or Brick Kiln shale.

The KC mine is planned as an open cut selective mining operation producing shale with an average run of mine grade of 123 litres per tonne with a cutoff grade to the retort of 90 litres per tonne. Prior to mine development the mine area will be cleared and topsoil stockpiled. During the first eight years of mine life, excavation will be by scrapers with no in-pit conveying facilities and a maximum depth of 75 metres. The scrapers will carry the ore to the crusher and the mine waste to the dumps. The Stage 1 layout is shown in Figure 1.2. Stage 1, operating at full capacity will typically process about 8.5 million tonnes of shale ore in the retort each year. Approximately 20 million tonnes of waste (including spent shale) will be moved to the dumps each year. A second mine pit and waste dump will be operated for Stages 2 and 3.

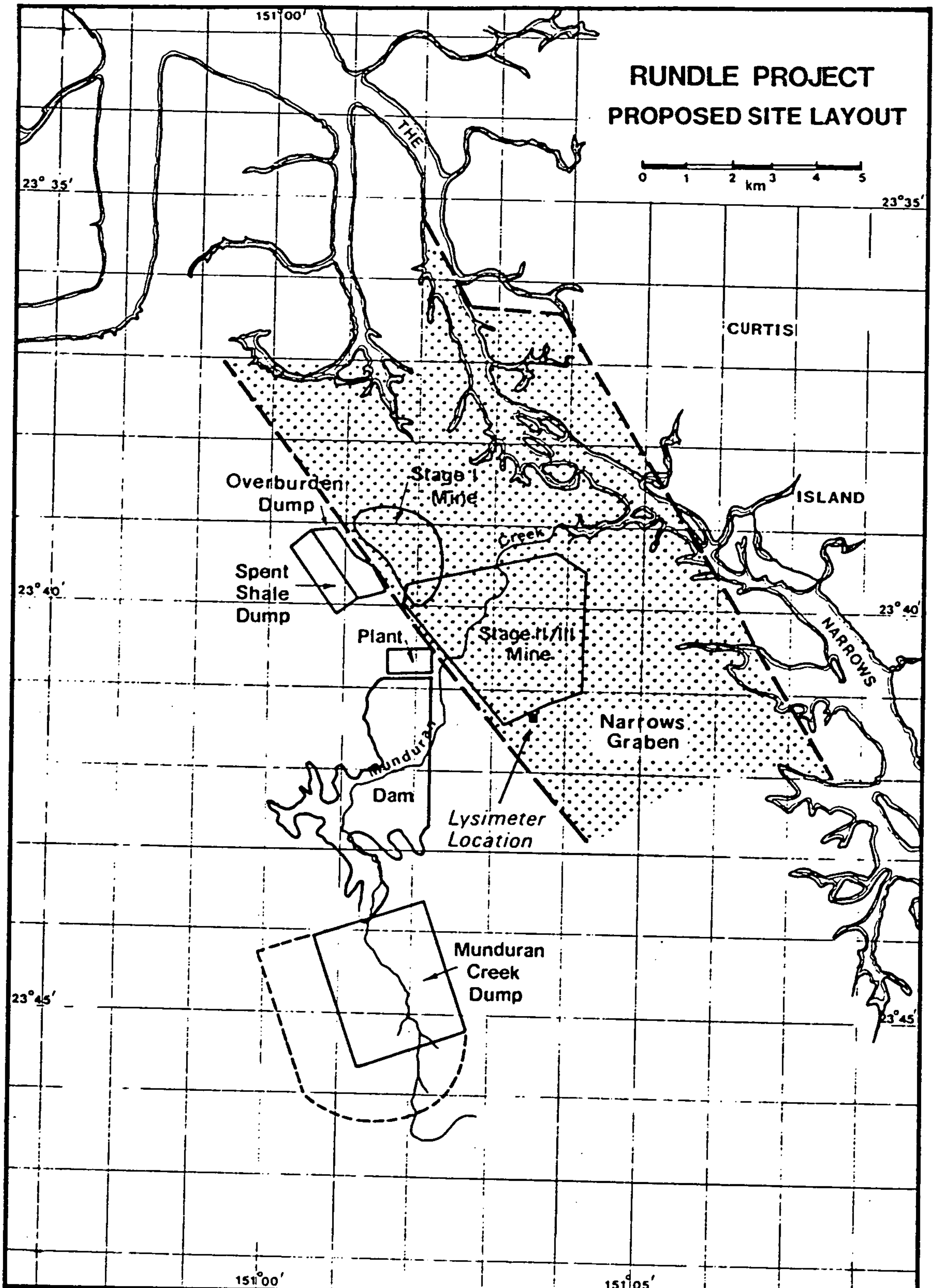


FIGURE 1.2 Rundle Project - Proposed Site Layout

The shale will be crushed to 98% minus 3.0 millimeters using a four stage crushing scheme and conveyed to the processing plant. Extraction of oil from the raw shale essentially involves heating the shale. Flue gas from combustion of carbon remaining on shale from which the oil has been removed will be used to dry and preheat the feed shale. The preheated shale will be fed to the fluid bed retort with hot shale from the combustor to provide heat to raise the raw shale up to retort temperature. Spent shale, raw oil and waste water are removed separately from the retort.

Some carbonate decomposition and other mineral reactions will also take place in the combustor. Gases containing H_2S and NH_3, hydrocarbon contaminated steam and solids will be incinerated in the combustor. The heat from the combusted shale cooler will be recovered and used to dry and preheat raw shale. This will cool the combusted shale to the disposal temperature of 60^oC. The combusted shale will be wetted to 16% moisture content for dust control and conveyed to the dumps. The water used to wet the combusted shale will be non-organic process water.

Water supply for Stage 1 will be by Gladstone town's water originating from the Awoonga Dam.

The raw shale oil will be dedusted and upgraded on site, sent by pipeline to Gladstone and refined in a conventional refinery offsite.

Present planning for the Rundle project, including environmental, technical, and economic planning, is based on a Stage 1, 25,000 tonnes per day, stand-alone project.

1.4.1 Solid Waste Disposal Planning Basis

The objective of the proposed dump design was to minimise leachate generation from the dump by minimising penetration of moisture from precipitation. This objective was to be achieved by a three way approach:

(a) Maximise evapotranspiration, by rehabilitation of the dump surface to the former native forest (mixed eucalypt) vegetation.

(b) Maximise runoff (constrained by erosion), by contouring of the dump surface.

(c) Minimise infiltration, by placing a claystone seal layer below the vegetated layer.

Two alternative dump designs formed the basis for further research. A base case where no organic water is disposed of with the solids (this is the planning basis) and a fallback/emergency case where there is limited co-disposal of stripped retort water with combusted shale. These dump designs are shown schematically in Figure 1.3.

Three types of solid wastes will be generated in significant volumes from development of the Rundle resource, the relative volumes of these predicted by the RCS are as follows:

	Stage 1 Mine years 1-8	Stage 2 & 3 years 9-24
Spent Shale	41%	39%
Overburden	54%	36%
Interburden	5%	25%

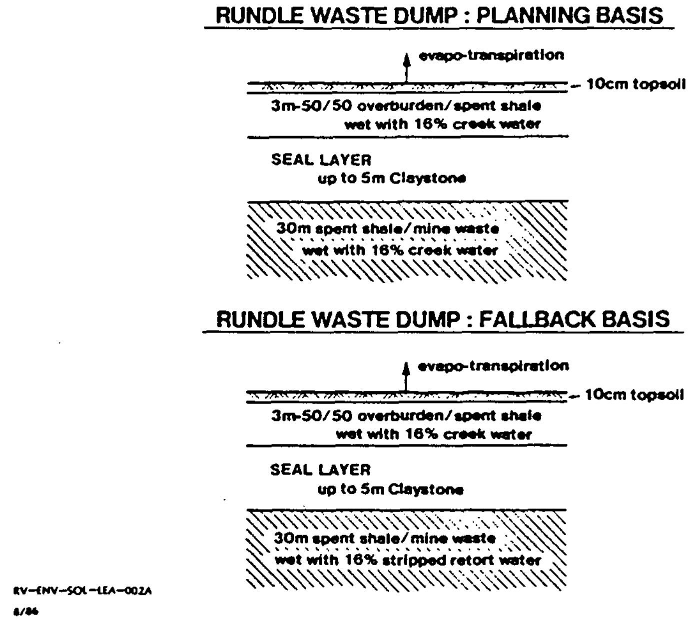


FIGURE 1.3 Rundle Waste Dump Planning Basis

Prior to dumping, combusted shale must be moistened for dust control. The Rundle Commercialisation Study Update planning basis is to use water from the flue gas venturi scrubbers to raise the moisture content to approximately 16%. The spent shale, upon disposal, remains unsaturated. Its saturated moisture content is in the range 50-60 weight %.

Thus the problem faced relevant to this thesis is that of the influence of vegetation on leachate generation from the Rundle Oil Shale waste dumps. The information base available for the Rundle Project is very good, so it remains to estimate the effect of vegetation on rainfall infiltration which will then be related to leachate production through the modelling work at the University of Queensland. It is first useful to put the thesis in the context of the research on leachate and also on evapotranspiration.

2. REVIEW OF LITERATURE

The literature relating to this thesis has been reviewed in three broad subject areas:

(a) Leachate generation from mining solid waste disposal piles.

(b) Rundle Oil Shale Project: Solid Waste disposal.

(c) Evapotranspiration and related issues.

2.1 Leachate Generation from Mining Solid Waste Disposal Piles

Most development work on leachate generation and treatment processes appears to have been carried out in the United States of America. The focus is usually on the specific case of the formation of acid leachate, often known as acid mine drainage (AMD) (Bell et al. 1982). The other area of research focus is leaching from radioactive wastes particularly in United Kingdom and the United States (Bell, Personal communication).

Little research has been done in Australia despite the fact that AMD problems are known to exist at some operating and abandoned mine sites. The USA research and experience is not directly applicable to most Australian mine sites because of the limited quantities of water available at many of the latter. The objective of most Australian leachate and water treatment is to achieve a standard whereby reuse is possible or discharge to a stream offering little or no dilution is possible (Bell et al. 1982). These are different objectives to those of the treatment plants and discharge standards in the USA where much greater volumes of water are often available for dilution.

Accordingly, and to remain within the scope of the thesis, the review of available literature on leachate generation from solid waste disposal piles has been restricted to the Australian situation.

The literature available tends to fall into one of two categories:

(a) Discussion of AMD, effects and treatment.

(b) Case studies either describing the problem at a particular minesite, or alternatively, the measures that were taken to alleviate a particular problem.

Little information was available on leachate not associated with AMD other than oil shale (see later). Appendix 1 lists some references which describe a number of Australian mining case studies which relate to AMD. The information presented in these case studies is not directly relevent to this thesis as laboratory studies have shown that leachates from the Rundle project are expected to be neutral or slightly alkaline (Tait and Cutler, 1987) with low toxicity. Therefore AMD is not likely to be of concern to the Rundle Project.

2.1.1 Vegetation and Control of Leachate Generation

There is extensive literature on rehabilitation and revegetation of mined land. Rather than list it here, the proceedings of the AMIC annual Environmental workshops (for example, AMIC 1986) are a good starting point for obtaining the approach and/or the latest techniques for effective rehabilitation as they have been applied to particular projects. Authors, such as Bradshaw and Chadwick (1980), and Collins (1983) have taken a more general, broadly based approach focused on description and on methodology.

Academic and other research is again project specific and an integration and synthesis of the varied experience in Australia has not been achieved.

Both the objectives of a particular rehabilitation project and the criteria to be used to determine whether these objectives have been met are often poorly defined (Collins 1983). Typical objectives include:

- replacement of original vegetation
- establishment of new, more productive vegetation
- sustainability
- dust control
- erosion control
- leachate control.

Using the specific case of leachate control it is widely accepted in the literature (Andersen 1980, Craze 1980, Andersen 1981, Harries and Ritchie 1987) that water uptake by vegetation reduces the quantity of water available in the soil available for other purposes. In spite of extensive work (reviewed later) by plant scientists, hydrologists, soil scientists and agricultural scientists quantifying plant water uptake, little has been done to apply this knowledge to mine waste dumps and the potential for leachate reduction.

Where a quantitative assessment has been made of the effect of an overall rehabilitation program, such as by Harries and Ritchie (1987), the individual effects of the various techniques used have not been quantified so the relative importance of reshaping, applying a claystone seal and revegetation to the reduction in the leachate produced cannot be assessed.

2.2 Rundle Oil Shale Project Solid Waste Disposal

2.2.1 Planning Basis

Commercial production of oil from the Rundle oil shale resource will produce large quantities of solid wastes which must be disposed of in an environmentally acceptable manner. Previous studies (Hakonson and White 1980, Brown and Rowley 1983, Moore and Thompson 1984) identified a number of solid waste disposal issues requiring research prior to any commercial development of an oil shale project. Paramount among these issues was the quantification of the flow and composition of any leachate produced from the waste dumps.

The current design objective for the Rundle waste dumps is for maximum runoff, maximum evapotranspiration and minimum infiltration of rainwater into the dump in order to minimise the quantity of leachate produced (Cutler et al. 1986). The design objectives will be achieved by dump shaping, incorporating a claystone seal layer over the dump covered by a stable surface layer and vegetation (Tait 1986b, Tait and Cutler 1987). Organic laden water will be excluded from the waste piles. Establishment of the claystone seal layer and vegetation will be carried out as the waste pile progresses so that the area of waste exposed to atmospheric conditions is minimised. A sketch of the present waste dump planning basis was presented as Figure 1.3.

Investigation into the dusting characteristics of Rundle combusted shale have shown that 16% moisture addition to the combusted shale prior to disposal would be sufficient for dust control and that chemical additives were not required (Esso Australia Ltd., unpublished data 1986).

The initial moisture content of the combusted shale in the waste piles has been found to influence leachate generation. Higher initial moisture content results in the production of a slightly more dilute leachate slightly earlier than from a combusted shale pile with a lower initial moisture content (University of Queensland, unpublished data 1987). One of the objectives of the University of Queensland modelling will be to determine whether the leachate formed will vary in concentration from background levels at Rundle site.

2.2.2 Revegetation Studies

An integrated series of revegetation studies was carried out with the objective of identifying the most effective technique for establishing native vegetation on the waste dumps whilst meeting the needs of dust control and erosion control. The sequence of research included (Marshall et al. 1983, Marshall 1984, Marshall et al. 1987):

(a) Preliminary information gathering (Marshall and Johns 1982).

(b) Surveys of existing vegetation, including species association, distribution and seed capacity for the area (Burgman and Thompson 1981a, Burgman and Thompson 1981b, Marshall and Koch 1982, Marshall et al. 1985).

(c) Investigation into the properties of soils and wastes (Marshall and Johns 1982, Marshall and Koch 1982, Johns and Marshall 1984, Marshall 1985, Tait and Cutler 1987).

(d) Seed collection and determination of germination characteristics (Marshall and Johns 1982, Marshall et al. 1982, Marshall and Koch 1982).

(e) Pot experiments performed to obtain species growth responses on different wastes to various amounts and combinations of fertilizer and topsoil (Marshall and Johns 1982, Marshall _et al_. 1982, Koch _et al_. 1984).

(f) Pilot field trial carried out on waste dump to determine the quantity of fertilizer required for field conditions (Marshall and Koch 1982).

(g) Measurement of rainfall, runoff and erosion (Marshall and Koch 1982, Koch _et al_. 1983, Koch _et al_. 1984, Marshall _et al_. 1985).

(h) Major field trial performed on waste dump, with treatments combining different seed mixtures, wastes and fertilizer application rates (Marshall and Koch 1982, Koch _et al_. 1983, Johns and Marshall 1984, Koch _et al_. 1984, Marshall and Koch 1985, Marshall _et al_. 1985).

This research program identified two areas of particular importance when developing techniques to meet the Rundle rehabilitation objectives :

(a) The moisture characteristics of the material (namely water storage and infiltration characteristics).

(b) The germination and growth characteristics of the species used.

By manipulating seeds, fertilizer and waste material a range of vegetation cover can be established. The present planning basis (Cutler 1986) consists of:

(a) Using a mixture of combusted shale, 16% water and overburden in the surface 3 to 5 metres and a 0.1 metre topsoil layer on the surface (ensures good soil water storage capacity).

(b) Seeding with a mixture of grasses and woody species.

(c) Applying NKP fertilizer once.

This strategy should give early growth of pasture grasses providing surface stability, dust and erosion control, followed by (after 6-12 months) growth of woody species such as Acacias and Eucalypts.

Further work was carried out to analyse the chemical composition of plants grown on wastes during the field trials mentioned above (Tait 1986a). No toxic concentrations were recorded in the plants analysed during the study. All concentrations were similar to results available for the same species grown under a glasshouse on a sandy loam soil or pasture conditions.

2.2.3 Leachate Studies

A number of studies have investigated the potential for leachate production from the waste materials produced by the Rundle Oil Shale project.

Small scale batch and column leaching studies identified solute dissolution, cation exchange, solution speciation and hydrodynamic and unsaturated flow effects to be the mechanisms of most significance to the leaching of inorganic components from Lower Ramsay Crossing Shale processed in the Lurgi pilot plant retort (Krol *et al*. 1983, Geronimos *et al*. 1984, Krol *et al*. 1985). The generation and transport of the major components (calcium, magnesium, sodium, potassium, chloride, and sulphate) in the leachate from a column of retorted shale was described. Model predictions are reported to compare well with experimental results (Krol *et al*. 1985).

Comparison with leachate data from combusted shale produced from the Exxon pilot plant (University of Queensland, unpublished data 1986) show similar trends in leaching of inorganic ions (Tait and Cutler 1987). From this it was concluded that the same mechanisms were controlling the rate of leachate generation from the two shales, but the total quantity of salts leached from the Exxon retorted shale was greater than that from the Lurgi shale. Further studies are in progress to investigate this (i.e., the present leachate program).

Other column leachate studies (Jones and Chapman 1983) were carried out on raw shale and mine waste. Some samples of raw shale generated a low pH of 2.3 and a leachate containing elevated concentrations of nitrate, selenium, manganese and boron. This was possibly due to an elevated acidification potential resulting from pyrite. This did not occur when raw shale was combined with spent shale and is not expected to occur in the dumps due to waste pile construction and material placement

The composition of the leachate has been examined and found to contain very small quantities of complex organics making them very difficult to analyse (Batley 1983, University of Queensland unpublished data 1986). Separate studies are ongoing to investigate techniques for analysing the leachate composition.

The planning basis, if research results predict the formation of leachate, is to install a series of drains prior and during dump construction to collect and treat the initial leachate (if there is any produced). Thus the high salinity waters produced during the first pore volume will not come into contact with the environment. In spite of this, two studies have been carried out to assess potential impacts if the initial leachate does come in contact with the environment.

An investigation was carried out into the transport of metals of environmental interest released into a creek bed on the Rundle Oil Shale project (Chapman et al. 1984, Considine 1987). It was shown that mobility of the ionic chemical components varied, some being adsorbed upstream, others being transported downstream for greater distances. Thus any chemical or biological effect could depend on downstream distances.

Preliminary tests were carried out to assess the toxicity of raw and spent shale leachate (Mann and Florence 1986). The marine diatom (**Nitzschia closterium**) was used for the screening tests. Leachates from raw and retorted shales were found to have low toxicity. In some cases algal growth was enhanced, probably because the leachate contained nutrients such as iron, nitrogen and phosphorus.

Leachate studies are continuing to investigate the leaching of trace components and the major organic components in addition to the major inorganic components considered by the earlier studies. The ongoing leachate program consists of laboratory column studies and field lysimeter studies. The objective of the field lysimeter studies was to test the applicability of laboratory studies to larger columns under field conditions (Figures 2.1, 2.2, 2.3 and 2.4). Tait and Cutler (1987) and Cutler et al. (1986) describe the lysimeter project in detail.

Eight lysimeters were installed at the Rundle site (Figure 1.2) in an area with similar meteorology to the proposed waste pile location. Figure 2.1 shows the layout of the lysimeter site.

A schematic of a lysimeter is shown in Figure 2.2. It is three metres deep, with a diameter of two metres. The bottom is conical with a central drainage outlet. The lysimeters were installed below ground so that the top was level with the ground surface (Figures 2.3 and 2.4). An access trench lined with

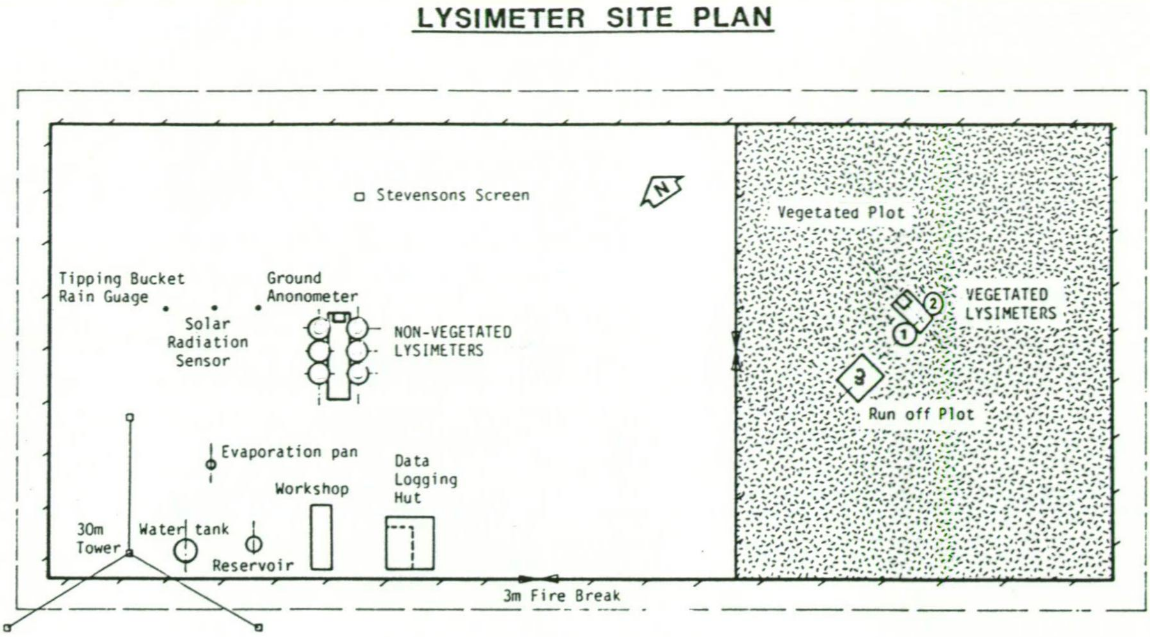


FIGURE 2.1 Plan of Rundle Lysimeters Showing Vegetated and Non-vegetated Lysimeters

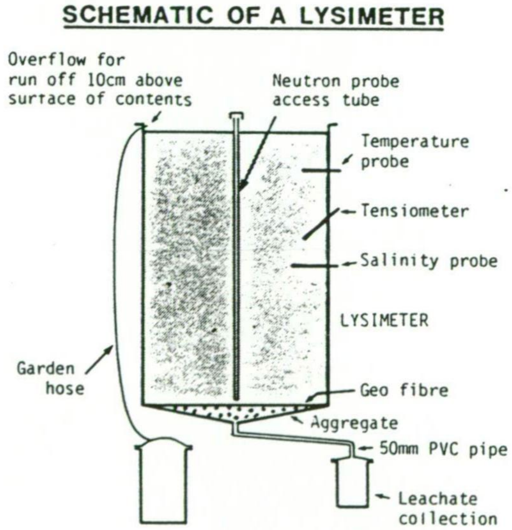


FIGURE 2.2 Schematic of Lysimeter Constructed of Fibreglass

FIGURE 2.3 Aerial View of the Rundle Lysimeters: February 1986 Vegetated Lysimeters

FIGURE 2.4 Aerial View of the Rundle Lysimeters: February 1986 Non-vegetated Lysimeters

treated timber was constructed between the lysimeters. Temperature probes, conductivity probes and tensiometers were inserted into the lysimeters, from the access trench, to monitor continuously the movement of wetting fronts through the lysimeters. These instruments were connected to a data logger which also monitors the meteorological station. The data logger and instruments were remotely monitored from Brisbane, Sydney and Tasmania, and supplemented by monthly site visits for quality control and manual data collection.

Neutron probe access tubes were installed in each lysimeter and a Campbell Pacific Nuclear 501 DR neutron probe used to track the changes in moisture profile.

Materials and procedures used to fill the lysimeters and the techniques used to revegetate the surface of lysimeter 2 aimed to simulate the large scale waste pile as closely as possible. The installation has been exposed to natural wetting and drying cycles since January 1986.

In conjunction with these studies, an integrated model of the proposed waste piles will be developed. The model will couple an unsaturated water flow model to a solute adsorption/desorption and transport model which includes major inorganic elements, trace elements and some organic compounds. The model will cover all parts of the waste piles including evapotranspiration (Tait and Cutler 1987, University of Queensland, unpublished data 1987). Data from the laboratory columns and field lysimeters will be used to verify the model.

The model is being developed by University of Queensland Department of Chemical Engineering, and the results presented in this thesis will be used as inputs into the model.

2.3 Soil-Vegetation-Water Interactions

2.3.1 General

There is a vast body of literature on soil-vegetation -water interactions. Many basic biology and soil physics texts such as Hillel (1980a, 1980b, and, 1982) give a comprehensive introduction to the topic. Rose and Byrne (1972) give a brief introduction. For the purposes of this thesis the portion of the work that could be categorised under evapotranspiration and related topics is of most interest. Two recent conference publications (Sharma 1984, American Society of Agricultural Engineers 1985) form the basis of this review which seeks to cover, albeit briefly, the scope of recent (and some not so recent) research as presented in papers, rather than to be encyclopedic in the presentation. This is not the first time this approach has been used (Philip 1966).

2.3.2 Components of Evapotranspiration

Firstly a note on terminology, although evapotranspiration is widely used in the literature it has a tendency to lead to confusion as it is not always apparent whether the author is referring only to evaporation from leaves or to evaporation from the soil or free water as well. McIlroy (1984) and Montieth (1985) are among those who advocate the use of the all-embracing term evaporation (E) in place of evapotranspiration. Subscripts can be used to denote particular components of evaporation such as soil (E_S), intercept (E_I), leaf or foliage (E_L or E_F) evaporation (also known as transpiration (E_T)). For consistency with most of the literature evapotranspiration is used in this thesis as the "all-embracing" term.

Some research has been carried out to determine the relative significance of each of the three components of evaporation such as that presented in Denmead (1970).

2.3.2.1 Evaporation of Intercepted Precipitation

Direct evaporation can occur whenever there is water present on the surface of the leaves, stems or branches of the vegetation and on the soil or litter. The most frequent source of this water is precipitation, but can also be condensation of dew or interception of mist or cloud droplets. Intercepted precipitation is the difference between gross precipitation and that reaching the soil (i.e., throughfall plus stemflow). Estimation of interception is subject to error because of the difficulty of relating measurement of stemflow from a particular plant or sample of plants to a standard such as stem flow per basal area per hectare (Crockford and Johnson 1983).

The rate of evaporation of intercepted rainfall primarily depends on the aerodynamic conductance and on the atmospheric humidity close to the surface (Stewart 1984).

2.3.2.2 Transpiration

Water moves from the soil to the air through plants along a gradient of water potential containing a number of resistances (Philip 1966). The pores known as stomata are the final resistance that restrict the flow of water vapor into the atmosphere. Opening and closing of stomata in response to such things as light, atmospheric humidity deficit, soil moisture deficit and carbon dioxide concentration appears to be the major mechanism by which plants control their water balance. Stomatal resistance depends on age and position of the leaves on the plant (sunny, shaded, height in the canopy) (Stewart 1984).

2.3.2.3 Evaporation from Soil

Evaporation from bare soil depends on a combination of meteorological and soil factors. Three conditions are required: a supply of heat to the evaporating surface, a vapor pressure gradient between the soil and the atmosphere (including vapor transport away from the surface) and a supply of water from the soil to the surface. Thus the rate of evaporation is determined by the external evaporativity or by the soil's own ability to deliver water, whichever is the lesser, and therefore, limiting factor (Hillel 1982).

Mathematical simulation of evaporation from bare soils, such as that by Markar and Mein (1983), has given reasonable estimates of daily and instantaneous evaporation. Rose (1968) has presented techniques for calculating soil evaporation. An example of the determination of evaporation from the soil and litter layers is presented by Greenwood et al. (1985).

2.3.3 Measurement of Evapotranspiration

A huge variety of techniques for measuring evapotranspiration are presented in the literature. Some are more appropriate in terms of cost, convenience or accuracy for measurement of evapotranspiration at a particular spatial scale or over a particular time scale (Rose and Sharma 1984). No single method has clear advantages in all contexts so the conceptual basis, assumptions, limitation and strengths of each method need to be understood in order to make a suitable choice of method for a particular situation.

Summaries of available methods are presented in Stewart (1984), and Rose and Sharma (1984) although more extensive reviews are referenced by these authors. An extensive experimental investigation of evapotranspiration methods is presented in Ljungkull and Baker (1982). Rather than repeat their summaries this discussion is limited to mentioning the major topics.

The methods of measuring evapotranspiration can be grouped into three categories: micrometeorological methods, hydrological methods and plant physiological methods. The limitations on these groups varies but is often related to the difficulty in obtaining representative data.

Micrometeorological methods rely on the measurement or estimation of parameters of the atmosphere, such as temperature, humidity, and flux gradient relationships adjacent to the evaporating surface. There are a variety of aerodynamic, energy budget and combination methods which include:

(a) Eddy correlation method. The conceptual basis is generally accepted but the instrumentation required restricts its application to a research context.

(b) Bowen ratio method. Measures rather than estimates evapotranspiration, requires spatial differences in air temperature and humidity to be measured simultaneously. This is a particular example of an energy budget technique, other examples are presented by Denmead (1964) and Miranda et al. (1984).

(c) Combination methods (energy balance and transport considerations are combined). The Penman-Monteith equation is widely used in estimating evapotranspiration from closed canopies with non-wetted surfaces, inaccuracies arise for open canopies or heterogeneous communities (Monteith 1980). Aston (1984) presents a test of the combination equations.

Hydrological methods rely on the water balance of an area such as:

$$P = Q + E + S + D$$

where: P = precipitation, Q = runoff, E = evapotranspiration, S = change in water content of the soil and D = drainage to groundwater. The method of measuring or estimating the components depends on the time scale over which the balance is to be determined and the size of the area. The methods include:

(a) Water balance of catchment area. This is usually performed when the soil moisture deficit is the same; drainage is often assumed to be zero.

(b) Zero flux plane method can be used where there is drainage if the depth of the zero flux plane can be obtained from measurements of the soil tension profile.

(c) Lysimeter method. This can be used on a small scale to measure all the components of the water balance. The sophistication of lysimeters varies from drainage lysimeters to complex weighed lysimeters.

Plant physiology methods are varied. There is some debate as to the accuracy of individual methods such as the ventilated chamber method. The reader needs to be cognisant as to which component of evapotranspiration they are measuring. A sample of the plant physiological methods includes:

(a) Porometry, which involves a small chamber clamped over a group of leaves and measurement of the flow of water from the plant material. This gives, with suitable calibration, an indication of the stomatal resistance (Byrne et al. 1970, Berkowitz and Hopper 1980).

(b) Ventilated chamber methods, which have been used to enclose entire plants or trees and the increase in water vapor measured to give transpiration from the plant.

(c) Tracer techniques, both heat pulse and radio-isotope methods have been used to record the travel time of water in plants. These have also been referred to as sap flow methods.

(d) Cut tree method, which can be used to determine evapotranspiration from individual trees by cutting the trunk under water and measuring the amount of water required to maintain a fixed water level in the tank in which the tree sits.

(e) Pan coefficient methods, which assume that evapotranspiration is related to the product of pan evaporation (a standard meteorological measurement) and a coefficient. The empirically determined coefficient is incorporated to account for the particular type of vegetation or bare soil and takes into account Leaf Area Index (leaf area per unit area of land), type and age of vegetation and so on (Eagleman 1967).

2.3.4 Modelling Evapotranspiration

A wide range of evapotranspiration models have been developed. The objectives of these models vary from provision of a management tool to obtain consistent opinions, to process models to give an understanding of the system or to interpret experimental results. And similarly a variety of techniques has been used to generate these models. However, as with measurement of evapotranspiration, use of models requires the researcher to be cognisant with both the assumptions within the model and with the data input into the model (Rose and Sharma 1984).

Models can be experimentally derived such as those described by Eagleman (1971), and Dunin and Aston (1984) or theoretically derived, for example, McNaughton and Jarvis (1984).

Caution must be exercised when taking results from a particular catchment or model and applying them directly to another location as this has often proved to be an unreliable method of obtaining evapotranspiration information (Kozlowski 1983).

2.3.5 Factors Which Influence Evaporation

A number of the factors which influence evaporation are listed in order to gain insight into the complexity of the subject.

(a) Radiational energy balance determines the input of energy into the evaporation process. It is the net balance of incoming short and long wave radiation and reflected shortwave and emitted long wave radiation. The incoming radiation is surface independent in contrast to the outgoing which depends on local surface characteristics (Stewart 1984).

(b) Efficiency of removal of water vapor away from the surface depends on meteorological conditions such as wind speed, temperature, and humidity, as well as the surface roughness which varies with the type of vegetation (Denmead and Shaw 1962, Denmead 1964, Stewart 1984).

(c) Vegetation community characteristics such as homogeneity, heterogeneity or a single tree.

Each case requires a different approach to the determination of evaporation (Rose 1976), for example, the Pennman-Monteith equation is useful for homogeneous communities but there is debate as to its accuracy in the other cases (Rose 1984).

(c) Vegetation characteristic such as size, age physical structure, Leaf Area Index, interaction with neighbors and other species and seasonal growth habits determine relative quantities of interception, stem flow, throughfall and evaporation. Leaf Area Index is felt to be significantly related to evaporation (Watson 1958), but accession in species such as eucalypts may influence this (McColl 1966).

(e) Soil properties such as sorptivity and hydraulic conductivity influence both infiltration, time to ponding (runoff) and evaporation (Rose _et al_. 1965, Hamilton _et al_. 1983). Soil cracking increases initial infiltration rates markedly, as modeled by Davidson (1984). Soil characteristics also influence deep drainage.

(f) Available soil moisture is important as water stress reduces transpiration and bare soil evaporation. Research has been undertaken with crops and pasture to determine relationships between evapotranspiration and available moisture (Butler and Prescott 1955, Denmead and Shaw 1962).

(g) Runoff influences water available for evapotranspiration. Models have been developed to predict runoff (Sukvanachaikul and Laurenson 1983). Ground cover effects occurrence and magnitude of runoff (Lang 1979). Runoff has been used to give general indications of the hydraulic properties such as infiltration of a catchment (Campbell 1981).

(h) All of the above are affected by spatial variability of soils, aspect, vegetation, slope and so on, (Sharma 1983, Burch et al. 1983).

2.3.6 Synthesis

Evapotranspiration research covers a wide range of disciplines each with its own focus and objectives. This feature is reflected in the diverse techniques that have been developed to carry out investigations.

Saxton and Howell (1985) pointed out that most current theory was developed in the mid-sixties, or earlier. Instrumentation and technology for collecting, analysing and modelling data has advanced very rapidly. This has been reflected in the huge quantity of literature produced. However, "this information bulge produced more progress in doing than thinking", reflected in the production of "more methods than theories" (Saxton and Howell 1985). This is typified by the predominance of case studies compared with general applications and development of generally applicable theories.

There are two main thrusts of evaporation research:

(a) A focus on the plant physiology of water and plant interaction. Concerns are such things as the behavior of plants when the soils are dry, crop yields, and irrigation.

(b) A focus on the water remaining in the soil as a resource for other purposes such as groundwater recharge. Interest is mainly in wet soils when water movement is able to occur.

Evapotranspiration research is important in trying to predict how changes in land use of a catchment may alter the hydrological equilibrium of the catchment by altering components of the water balance. These land use changes include replacing perennial deep rooted forest with shallow rooted seasonal agricultural vegetation, and by mining with the subsequent disposal of mine wastes.

3. DEVELOPMENT OF A MODEL FOR THE INFLUENCE OF VEGETATION ON WATER FLOW: THE RESEARCH PLAN

3.1 Development of the Research Plan

The objective of the research plan is to present a strategy, incorporating knowledge gained from the literature review, to test the hypotheses put forward in Chapter 1.

Selection of the research plan was constrained in some respects by this project, being one element of an extensive program which was designed to model the quality and quantity of leachate from the proposed Rundle waste piles. The most practical techniques to use were those already in use or available to the Rundle project.

Predictive modelling was the focus of the overall research program so it had to be fundamental to the development of the research plan. Review of literature, availability of meteorological data including precipitation and pan evaporation, availability of a neutron probe for soil moisture determination and the existence of vegetated plots containing vegetation of a variety of ages determined the selection of water balance techniques as the most appropriate for this project. Calculation of the water balance should provide evidence to support or refute both hypotheses. Water balances should indicate whether vegetation affects the water available for leachate generation. Secondly, water balances applied cumulatively over a long period of time should be able to predict quantitatively the evapotranspiration from the vegetation and hence the water available for infiltration beyond the root zone.

Many other techniques are available for determining the evapotranspiration component more precisely (at least they are more precise in theory). Most of these methods rely on the accurate determination of plant physical factors such as stomatal resistance, or accurate measurement of surface heat flux and other similar parameters. The expertise, equipment and time required for these measurement was beyond the scope of this project.

Water balance determinations are very appropriate for the time frame both of data collection (months/years) and the aims of the predictive modeling (years/decades). Model development will be discussed in detail in Section 3.3.

After the water balance approach to modelling had been selected it was appropriate to determine the scope of the data required from the field studies.

The most important data requirements were pan evaporation and precipitation, Leaf Area Index (to give an indication of the relative evaporation potential of the vegetation), soil moisture content and material properties. The techniques used in the field studies and the results obtained are outlined in Chapter 4.

Seven plots containing vegetation of different ages were selected for the field studies:

Plot 1: An unvegetated lysimeter filled with combusted shale, 15% river water and overburden with a 0.1 metre soil layer on the surface.

Plot 2: A vegetated lysimeter, with contents the same as plot 1 except for a 1 metre compacted claystone seal layer in the bottom. This lysimeter was seeded in May 1986.

Plot 3: A vegetated plot next to the lysimeters, contents the same as plot 1.

Plot 4: A vegetated plot next to the lysimeters, where the soil was undisturbed except for combusted shale incorporated into the top 0.2 metre. Seeded at the same time and in the same way as plots 2 and 3.

Plot 5: A vegetated plot, in an area where the soil and subsoil layers have been disturbed, no combusted shale incorporated, seeded in 1983.

Plot 6: A vegetated plot, in an area where the vegetation had been cleared in 1981, and the soil was left undisturbed.

Plot 7: Mature vegetation typical of the Rundle area.

For each plot a vegetation survey was carried out, Leaf Area Index was determined and neutron probe access tubes were installed so that soil moisture could be determined periodically. A meteorological station was located close to plots 1, 2, 3, and 4.

The field studies and the information generated by each of them are shown in Figure 3.1. This is the research plan.

Field Data	Information Generated	
Neutron probe readings	Soil moisture store	
Lysimeter study	Drainage data	
Runoff Determination	Runoff data	
Met. data	Precip. / Evap. data	MODEL OF DRAINAGE BEYOND THE ROOT ZONE
Material charact.	Soil parameters	
Leaf Area Index	Relative transpiration potential	
Vegetation survey	Representativeness of vegetation	

FIGURE 3.1 Research Plan for Developing a Predictive Model for Drainage Beyond the Root Zone of the Revegetated Layer of the Proposed Rundle Waste Piles.

3.2 Why Develop a Model?

The Draft Impact Assessment Study Guidelines for the Rundle Oil Shale Project provided by the Queensland Mines Department in September 1985 requested information on the quantity and quality of all waste waters produced by the project including any seepage (leachate) from waste piles (Cutler 1988). Accurate and substantiated predictions of the quantity and quality of the leachates produced would provide part of the basis for the optimization of waste pile design and water management strategies. For example, the water management requirements would differ in complexity, scale and cost depending on both the quality of leachate produced and the quantity. Accurate predictions would permit optimum waste pile design, whilst inaccurate predictions would either waste money through overdesign of the dumps or allow increased potential for some environmental damage.

These were the motives leading to the decision to produce an integrated hydrological and chemical model of the waste piles. An alternative strategy that was considered was collection and analysis of field data from a "test dump" of several thousand tonnes of waste material. Collection of field data alone, even over an extended period, would not explain the leaching behavior of the waste piles subjected to climate patterns varying from those during the data collection period, as these variations could include such events as a 100 year storm or climate change leading to increased rainfall. If the processes that control hydraulic and chemical movement within the proposed waste pile were understood and incorporated into a computer model, variables such as precipitation, evaporation and temperature could be varied and the predicted waste pile behaviour under the changed conditions monitored. Thus the "test dump" approach was rejected in favor of modelling.

Similarly, if the evaporation from the vegetated layer on the surface of the dump can be modelled the output can be incorporated into the predictions of dump behavior from the rest of the model. This project was designed to consider the vegetated layer only. The results will be used as inputs into the hydrological and chemical models of the entire waste piles which are being developed by the University of Queensland.

The leachate models were developed to explain what is happening in small scale laboratory and field studies carried out over three years, and to predict what will happen in a large scale waste pile over a long time scale. The model of the vegetated layer refers only to field studies, and then seeks to predict long term behavior.

In the literature there is much debate as to the usefulness of ecological models, what type of models should be used, whether improved accuracy through larger and more complex models should be traded for improved applicability by simplification of already existing models. Wiegart (1975), Fleming (1979), Pielou (1981), Beck (1981), and Lindsay (1987) are but a few authors who have explored these issues. There are also many more specific papers that present a particular model or series of equations tested for one series of data, for example, Aston et al. (1980) and Philip (1984). The issues raised by these authors were taken into account before it was determined that a simple model was the most appropriate way to meet the objectives of this project. A simple model would enable the inherent assumptions to be readily understood and quantified, and was compatible with the resources and time available.

3.3 Model Development

The vegetated layer and associated water flows are shown in Figure 3.2. From this a series of assumptions were made:

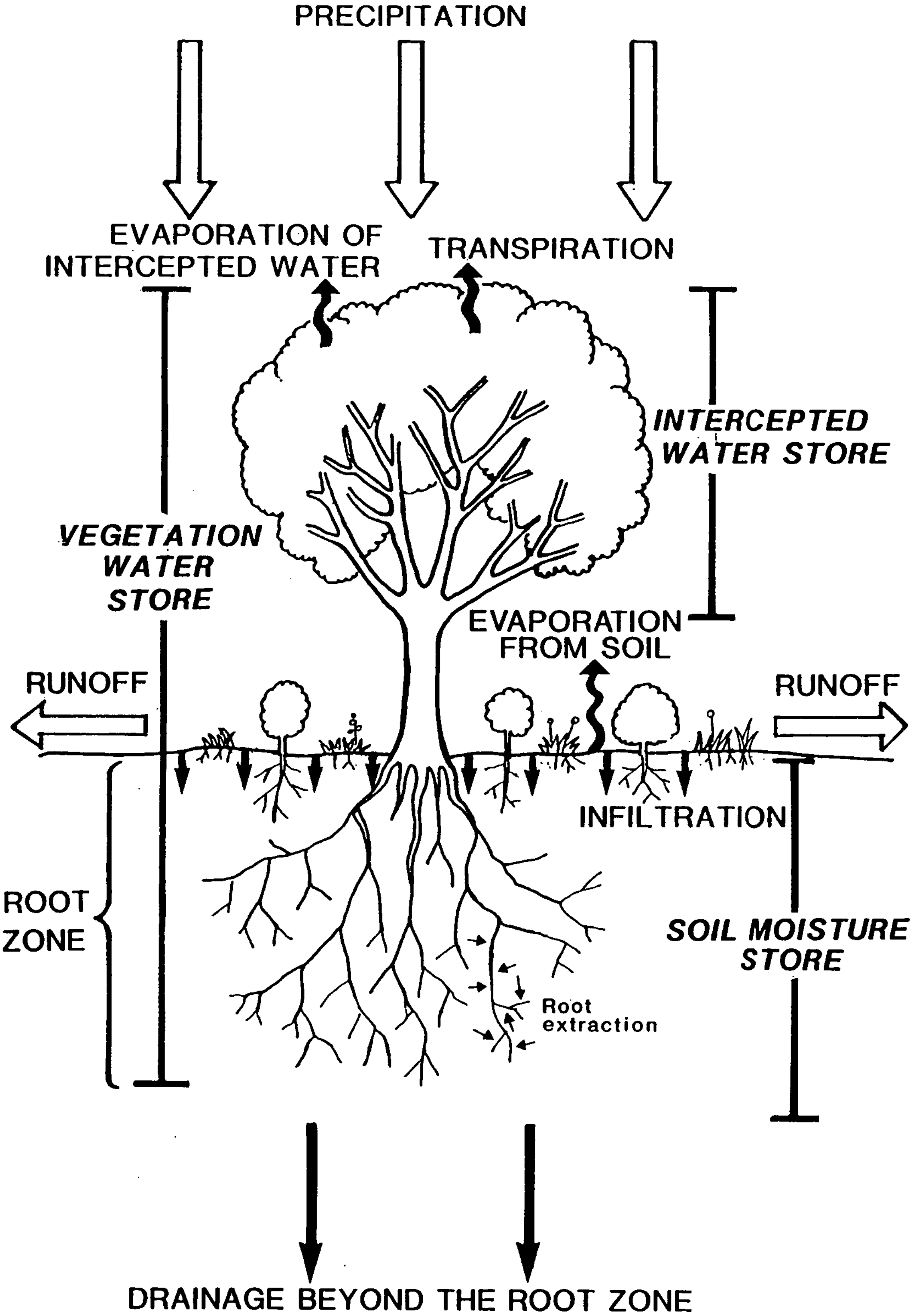


FIGURE 3.2 Water Flows in the Vegetated Layer

(a) Intercepted water store is negligible.
(b) The water stored in the vegetation is constant.
(c) Evapotranspiration is the sum of soil evaporation, intercepted evaporation and transpiration.
(d) The soil moisture profile can be represented as a soil moisture store for the zone of interest.

Incorporating these assumptions into the water flows shown in Figure 3.2, a "black box" type diagram of the water flows was developed (Figure 3.3). Equation 1 describes the water balance over the vegetated layer.

$$D = P - E - R - S \qquad (1)$$

where:
D = drainage beyond the root zone
P = Precipitation
E = Evapotranspiration
S = Change in soil moisture store
R = Runoff

A program was developed on an IBM personal computer to perform this calculation. The program performed the calculation iteratively over two days using one hour time intervals. A value for the initial soil moisture store was input from measured data. Drainage was set as zero and the soil moisture store allowed to increase or decrease according to the balance of water input from precipitation and water extraction from evaporation. When the soil moisture store exceeded field capacity the excess was assumed to flow as a flush of drainage reducing the soil moisture content back to field capacity. Runoff was assumed to be zero.

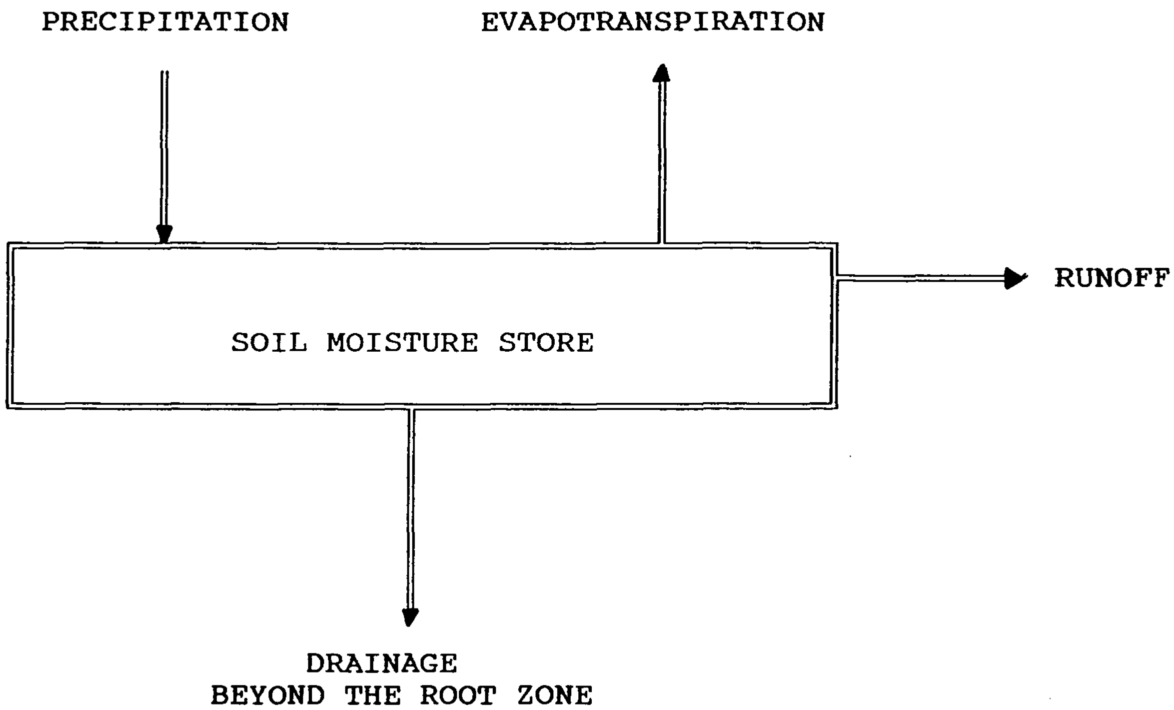


FIGURE 3.3
Schematic of Water Flows in the Vegetated Layer

Field capacity is an empirically determined parameter for particular materials and corresponds to the point at which water will move freely through the soil and drainage occurs.

That is :

if $\bar{\theta} < \theta_{fc}$ - very slow leachate (2)

if $\bar{\theta} > \theta_{fc}$ - flush of leachate (3)

where $\bar{\theta}$ = mean soil moisture content

θ_{fc} = soil moisture content at field capacity

The assumption of a flush of leachate occurring when field capacity has been exceeded was regarded as a good model of the process, as shown in Figure 3.4.

Experimental data for precipitation, obtained from the field studies described in Chapter 4, provided input into the model. Pan evaporation data collected from the field studies was input into the model. A coefficient which related pan evaporation to potential evapotranspiration was determined from the literature and input into the model. The value of this coefficient varied with vegetation age, leaf area and vegetation type.

Figure 3.5 shows a sample output from the model. The process to be used to develop the model from this point to a fully functioning and verified model is shown in Figure 3.6.

The process of developing the model had commenced when personal communication with Dr. C. Rose directed attention to WATBAL, a water balance model developed by CSIRO. WATBAL was suitable for a personal computer, and made similar

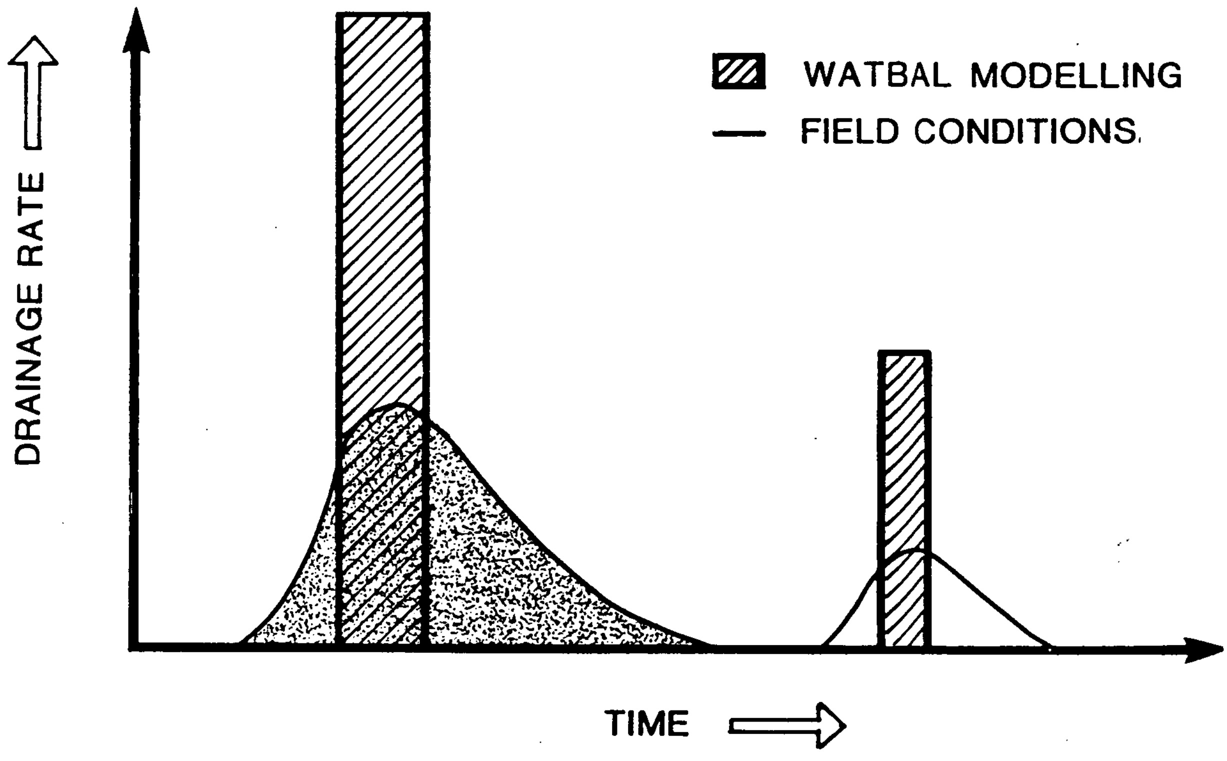


FIGURE 3.4 The Relationship Between Drainage Rate and Time as Represented by WATBAL Modelling Compared with Most Soils Under Field Conditions

Date	Time	Rain	Pan-E	Runoff	E/T fac	E/T	S	Tot.S	Drain
18.02.82	00:00				0.80	0.00	0.00	1560	0
18.02.82	01:00				0.80	0.00	0.00	1560	0
18.02.82	02:00				0.80	0.00	0.00	1560	0
18.02.82	03:00				0.80	0.00	0.00	1560	0
18.02.82	04:00				0.80	0.00	0.00	1560	0
18.02.82	05:00		0.3		0.80	0.20	-0.20	1560	0
18.02.82	06:00		0.3		0.80	0.20	-0.20	1560	0
18.02.82	07:00		0.3		0.80	0.20	-0.20	1559	0
18.02.82	08:00		0.3		0.80	0.20	-0.20	1559	0
18.02.82	09:00		0.3		0.80	0.20	-0.20	1559	0
18.02.82	10:00	5.00	0.0	0.0	0.80	0.00	5.00	1564	0
18.02.82	11:00	5.00	0.0	0.0	0.80	0.00	5.00	1569	0
18.02.82	12:00	5.00	0.0	0.0	0.80	0.00	5.00	1574	0
18.02.82	13:00	5.00	0.0	0.0	0.80	0.00	5.00	1579	0
18.02.82	14:00		0.3		0.80	0.20	-0.20	1579	0
18.02.82	15:00		0.3		0.80	0.20	-0.20	1579	0
18.02.82	15:00		0.3		0.80	0.20	-0.20	1578	0
18.02.82	17:00		0.3		0.80	0.20	-0.20	1578	0
18.02.82	18:00		0.0		0.80	0.00	0.00	1578	0
18.02.82	19:00		0.0		0.80	0.00	0.00	1578	0
18.02.82	20:00		0.0		0.80	0.00	0.00	1578	0
18.02.82	21:00		0.0		0.80	0.00	0.00	1578	0
18.02.82	22:00				0.80	0.00	0.00	1578	0
18.02.82	23:00				0.80	0.00	0.00	1578	0
19.02.82	00:00				0.80	0.00		1578	0
					0.80				

Initial soil moisture store
1560.00
Maximum soil moisture store
2340.00

Pan-E: Pan Evaporation
E/T fac: Coefficient based on vegetation to convert Pan-E to E/T
E/T: Evapotranspiration
S: Change in soil moisture store
Tot.S: Total soil moisture store
Drain: Drainage beyond the root zone

Figure 3.5 Sample Model Output

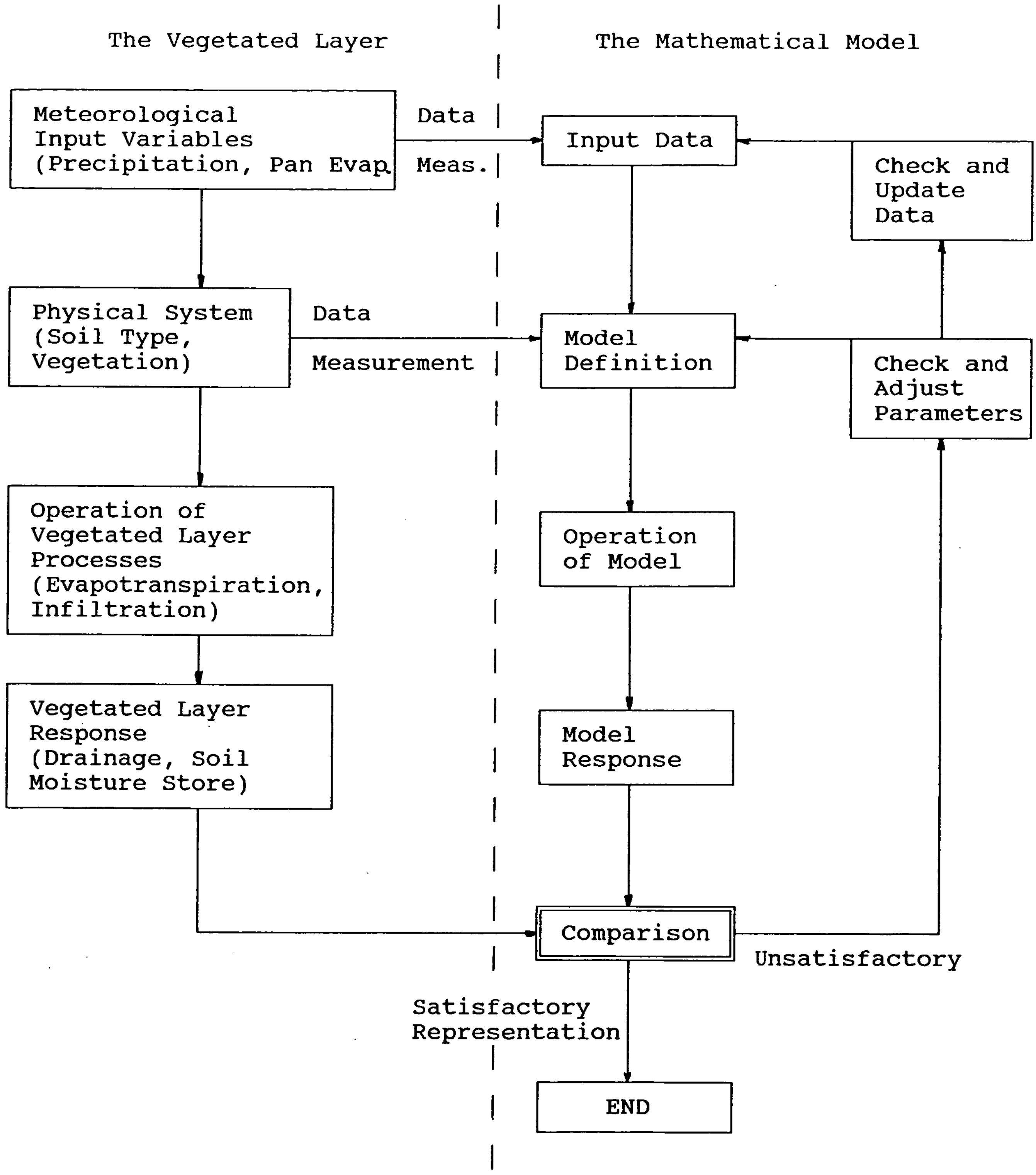


FIGURE 3.6

Mathematical Modeling Technique Adopted for the Model of the Influence of Vegetation on Water Flow assumptions to the model described above. WATBAL was examined closely as it was likely to be applicable to this project and had stood the test of time. It was first developed in the early 1960s. WATBAL was obtained from CSIRO together with instructions. WATBAL was tested, found to be suitable for this project, and adopted in order to meet the time constraints of this project. The steps proposed in Figure 3.6 to verify the model were still applicable to the project once WATBAL was adopted.

3.4 Description of WATBAL

WATBAL was developed to provide soil moisture and pasture growth information for regional climatic studies. It was developed as a simple water balance model requiring only readily available climatic data as input. More recently it has found more general use in forestry, hydrology and agriculture.

WATBAL was designed to apply on a weekly accounting basis to give estimates of weekly changes in soil moisture status. Maximum soil moisture storage (field capacity) was required as an input. Drainage was assumed not to occur until field capacity was reached.

Weekly rainfall was added to the existing soil moisture storage. Evapotranspiration was subtracted from the soil moisture storage. To determine evapotranspiration the potential evapotranspiration, that is, the relationship between maximum evapotranspiration for the vegetation type given freely available water and pan evaporation, had to be established. This relationship, the potential evapotranspiration, was expressed as a series of coefficients which could be varied for different seasons and vegetation cover.

The actual water demand on the soil moisture store for any one week, in contrast to the potential based on freely available water, depends on soil properties (expressed as a soil index), and current soil moisture relative to the maximum soil water store. The actual water demand was calculated as follows:

ADJ = 1 / (1 - exp (-SOIL))
REL = (current rain + storage)/maximum water storage
AET = ADJ * (1 - exp (-SOIL * REL))

where:
SOIL was an index for the type of soil (sample values are:
7.5 for sandy loam
3.5 for clay-loam
1.5 for clay).
ADJ was the adjustment to account for soil type.
REL was the soil moisture content relative to maximum.
AET was the coefficient which characterised the actual weekly water demand for that week.

To get the evapotranspiration for the week the pan evaporation was multiplied by the potential evapotranspiration coefficient and the actual weekly water demand.
The soil moisture storage for any particular week was the soil moisture storage for the previous week plus the rainfall for the week less the actual water demand. The soil moisture storage cannot be negative (was set to zero) and cannot exceed the maximum soil moisture store (the excess was drainage).

Further details of the WATBAL model are given in Keig and McAlpine (1974).

A number of constraints are inherent in the model:

(a) There was no provision for runoff until the maximum soil moisture store was exceeded. However, runoff could be incorporated manually if known by reducing the weekly precipitation by the known amount of runoff occurring in that week. If this was not done and runoff did occur the model would overestimate the quantity of drainage. This constraint on the model appears to have arisen as it was originally developed for pasture where much less runoff would usually occur than might be expected for other forms of land surface.

2. WATBAL was designed to use average weekly pan evaporation. Actual weekly pan evaporation for a series of years could be used by running the model sequentially for a series of years using the measured weekly evaporation in the input dataset for a particular year.

3.5 Modelling Strategy

The modelling strategy was developed in two phases. The objective of the first phase was to verify and calibrate the model using data from the field studies. This was followed by the second phase which focused on long term predictions of drainage beyond the root zone of the vegetation. The two phases were approached separately.

A series of runs were devised to test the model with available climate data using the vegetation and moisture data for each vegetated plot as other data inputs. The model required the following input data:

(a) Weekly (or daily) rainfall for the study period.

(b) Weekly pan evaporation (or mean weekly pan evaporation) for the study period.

(c) A series of weekly potential evapotranspiration coefficients which indicated the maximum evapotranspiration for a particular vegetation given freely available water.

(d) An assessment of soil properties, in the form of a soil index (described above).

(e) An initial soil moisture content for the soil profile of interest (an initial value for $\bar{\theta}$).

(f) Maximum soil moisture storage or field capacity (θ_{fc}).

The data for each sample plot were obtained from the field studies described in Chapter 4. Where particular data requirements (such as the weekly potential evapotranspiration coefficients) were not measured directly by the field data collection procedures, an estimate was made. The model was run and the output soil moisture and drainage compared with measured values. The input assumptions were refined until the model was consistent with measured soil moisture contents. This is discussed in Chapter 5.

The second modelling phase incorporated the physical parameters from the refined runs above with long term meteorological data in the form of average rainfall and pan evaporation data together with statistical variations of the long term average values. This produced an indication of the relative frequency of water movement beyond the root zone under specific vegetation and climate conditions.

In order to make these predictions the model was run for 2 to 4 years, commencing with the soil moisture contents measured in the field studies, until an equilibrium soil moisture content was reached. The term equilibrium soil moisture content was used to represent a situation where drainage, evaporation and rainfall over a year result in no net change in soil moisture content. From this point the model was run for one further year to determine the frequency of drainage beyond the root zone and to obtain an estimate of the volume of drainage.

The model requires weekly (or daily) rainfall and evaporation. The long term average rainfall and evaporation was available on a monthly basis. For the purposes of the model requirements the long-term monthly average rainfall and evaporation were assumed to occur uniformly over the month when the data were converted to weekly averages.

Variations in the average monthly rainfall and evaporation were also tested for the mature vegetation, plot 7. The variations used were ±10%, ±25% and ±50% of the average rainfall and evaporation. Rainfall and evaporation were varied separately for these runs.

The long-term modelling of plots 4, 5, and 6 used the average rainfall and evaporation. The pattern of the relative frequency of drainage beyond the root zone of the vegetation of different ages was compared.

Prior to examining the results of the modelling, the data collection undertaken as the field studies should be examined to gain an appreciation of the type of data available for input into the model.

4. FIELD STUDIES

The techniques used to collect the seven types of field data are described in this chapter and a summary of the results presented. These data were used as inputs into the model described in the previous chapter.

4.1 Soil Moisture Determination

Two techniques have been widely used for measuring soil moisture content:

(a) gravimetric sampling, and

(b) neutron moisture meter (neutron probe).

Gravimetric sampling involved destructive sampling of the soil of interest, weighing, drying and reweighing of the sample to determine the percent moisture. The neutron probe technique was suitable for repetitive in-situ measurements from any particular sample over a long period of time as destructive sampling was not required. The neutron probe was selected as the most suitable technique to follow changes in the water content of soil for this project, as well as for the entire leachate program.

4.1.1 Neutron Probe Technique

The neutron probe was designed specifically to measure the volumetric soil water content and the variation of soil water content over time, soil depth and spacial variations. The probe consists of a neutron source emitting fast neutrons and a means of detecting those neutrons scattered back to the source and detector region by the surrounding medium. Hydrogen atoms are the most efficient neutron scatters, so changes in the water content of a sample (and hence in the hydrogen atoms contained in water) are reflected by changes in the proportion of neutrons scattered back to the source and hence in the signal recorded. Thus the moisture content of soils and other materials can be determined. Density, clay content and other soil parameters can also affect the neutron count so a calibration is required for each material (Wilson 1982, Lal 1974). Details of the calibration and use procedures adopted for this project are discussed by Greacen (1981) together with the strengths and weaknesses of the neutron probe technique. Access tube installation in the study plots containing undisturbed soil profiles followed the hand auger technique described by Gilmour (1971).

4.1.2 Experimental Method

A Campbell Pacific Nuclear 501 DR moisture/density depth gauge was used for this project. To measure the soil moisture content the probe was lowered through a previously installed access tube into the soil. The probe was suspended at the desired depths for soil water measurements, and the number of neutrons scattered back to the source and detector over a predetermined period (say 34 seconds) was recorded. This was then compared with a standard count taken in a drum of water, and the ratio of the neutron count in water to the neutron count in soil determined and recorded in the memory of the instrument.

The aluminum access tubes required for the neutron probe operation were installed in the vegetated lysimeters and the runoff plot (ie: plots 1, 2, and 3) during construction of the lysimeters and run off plot (Cutler 1986). The other vegetated plots (i.e., plots 4, 5, 6, and 7) required a different approach as the sample areas were existing stands of vegetation and undisturbed soil profiles. After review of the available techniques, such as those described by Greacen (1981) and Gilmour (1971), the hand-augering method described by Gilmour was selected. Using this technique, which was somewhat labour intensive and slow, 3 access tubes were installed in plot 4, 3 in plot 5, 2 in plot 6, and 3 in plot 7. The material removed from the auger holes was kept and its moisture content determined. Neutron probe measurements were carried out on completion of the holes. This procedure provided the data necessary for a field calibration of the neutron probe. The technique used for field calibration is described in detail in Greacen (1981). Plots 1, 2 and 3 were calibrated using a different technique, a drum calibration. As the material used in each of plots 1, 2, and 3 was similar it was assumed that a single calibration curve would apply to these plots. The drum calibration involved packing a 0.9 metre diameter drum with the spent shale and overburden mixture used in the study plots at a range of known moisture contents and determining the corresponding range of the instrument. The material was packed at field density. Greacen describes the drum calibration technique, and a specific description calibration carried out for this project is given in Connell (1986).

Both the field and drum calibrations produce an equation of the form:

$$\theta_v = bn + a$$

where : θ_v = volumetric water content of the soil
n = ratio of neutron count in soil to neutron count in water
a, b are constants
(from Jayawardane et al. 1983)

When the field study was designed it incorporated a second calibration. A duplicate tube was installed in some of the plots, to increase the confidence in the calibration. At the time when the duplicate tubes were installed (five months after the initial tubes) the neutron probe was malfunctioning and unsuitable for calibration.

The field calibrations gave questionable results. For instance, they indicated that the moisture content of plot 5 was 20% and that of plot 6 was 15%. This level of moisture in the soil was too low to support vegetation growing on these plots. In order to obtain consistent and sensible results the calibration curve (developed using the drum calibration method) for a lysimeter containing overburden was used. This calibration was carried out for the general waste dump leachate program hydraulic modelling. This calibration gave moisture contents that could support vegetation and were much closer to those observed by Marshall and Johns (1982). As is discussed in Chapter 5 the variation in moisture content with time could be accounted for by precipitation and evapotranspiration.

The values obtained for the constants **a** and **b** are shown in Table 4.1. This equation and the constants associated with it were incorporated into the software developed for processing the neutron probe data.

TABLE 4.1 Neutron probe calibration coefficients

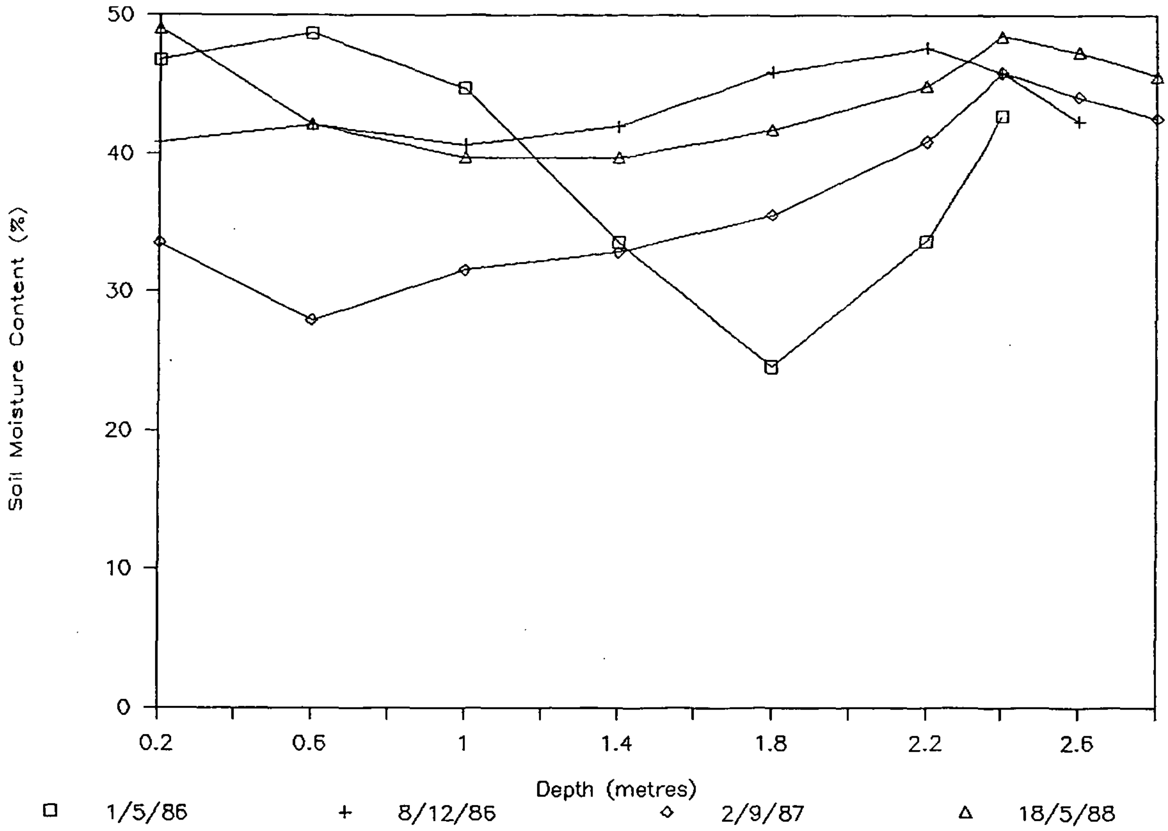
PLOT	No. of Tubes	**a**	**b**
1	1	.8325	.0295
2	1	.8325	.0295
3	2	.8325	.0295
4	3	.8167	.0282
5	3	.8167	.0282
6	2	.8167	.0282
7	3	.8167	.0282

The neutron probe was run at approximately one month intervals at prescribed depths in each access tube. The neutron count ratio was recorded by the probe at each depth and later downloaded to the Rundle IBM computer for further processing. L. Connell developed the software for processing the neutron probe data after it had been downloaded onto the computer. This software uses the calibration equation to calculate the soil moisture profile and the total moisture content of the soil profile.

4.1.3 Results and Discussion

An example of the data produced over time is shown in Figure 4.1 These data is from plot 2. The total moisture contained in the soil above a particular depth is calculated by integrating the soil moisture profile over that depth (i.e., determining the area under the curve). The moisture profile and soil moisture content vary with time. This plot has a 1 metre deep claystone seal layer in the bottom This is reflected by the more consistent soil moisture profile below 2 metres.

Figures 4.2 to 4.7 show the total moisture content of the vegetated plots over the period of data collection. It is interesting to note that all the plots reflect a dry period from February 1987 to June 1987, which was then followed by a period of increasing moisture content. This was first thought to be consistent with two months (January and February 1987) of relatively low rainfall in the order of 30% of the average for this period, and corresponding high evaporation. The model runs discussed in Chapter 5 do not predict these low soil moisture levels during this period. The low frequency of readings during this period was due to neutron probe malfunctions and the need for repairs on several occasions. These malfunctions are the most likely reason for the unexpectedly low soil moisture contents during the first half of 1987.



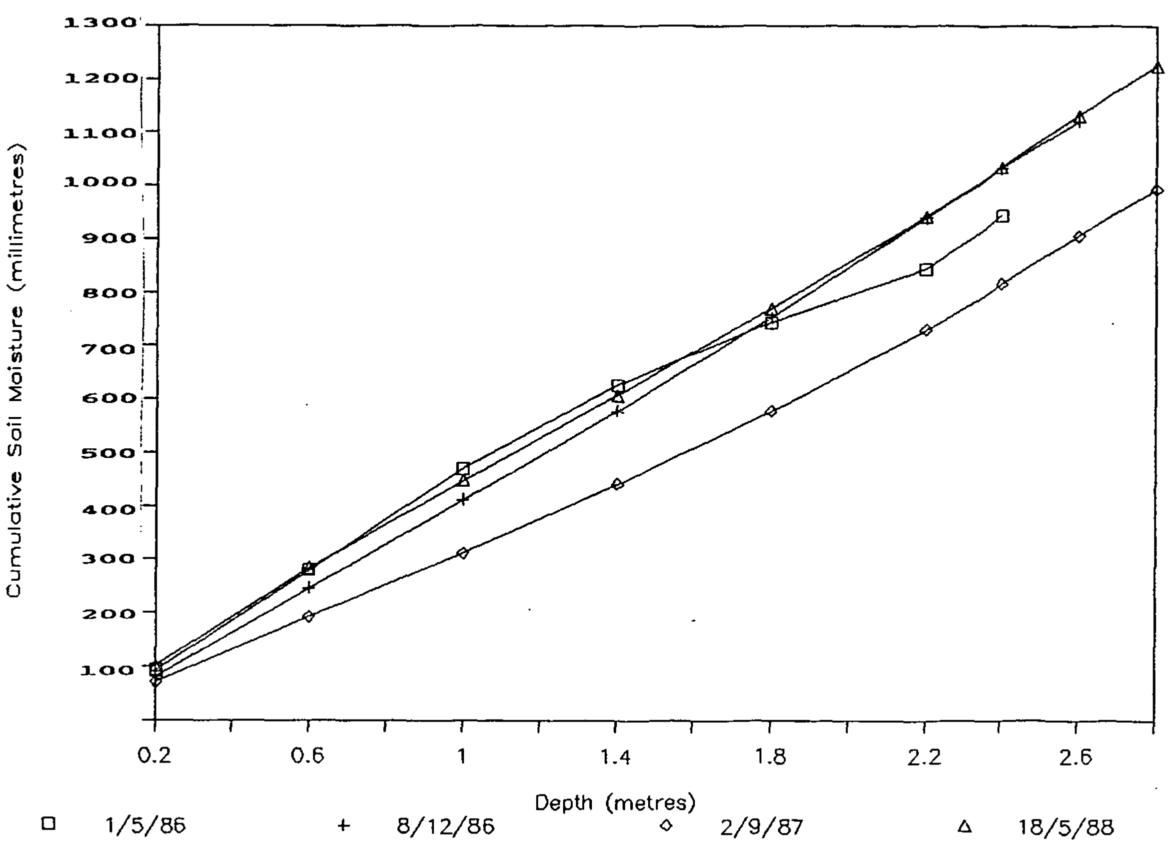


FIGURE 4.1 The Variation of Soil Moisture and Total Cumulative Soil Moisture With Depth, Plot 2

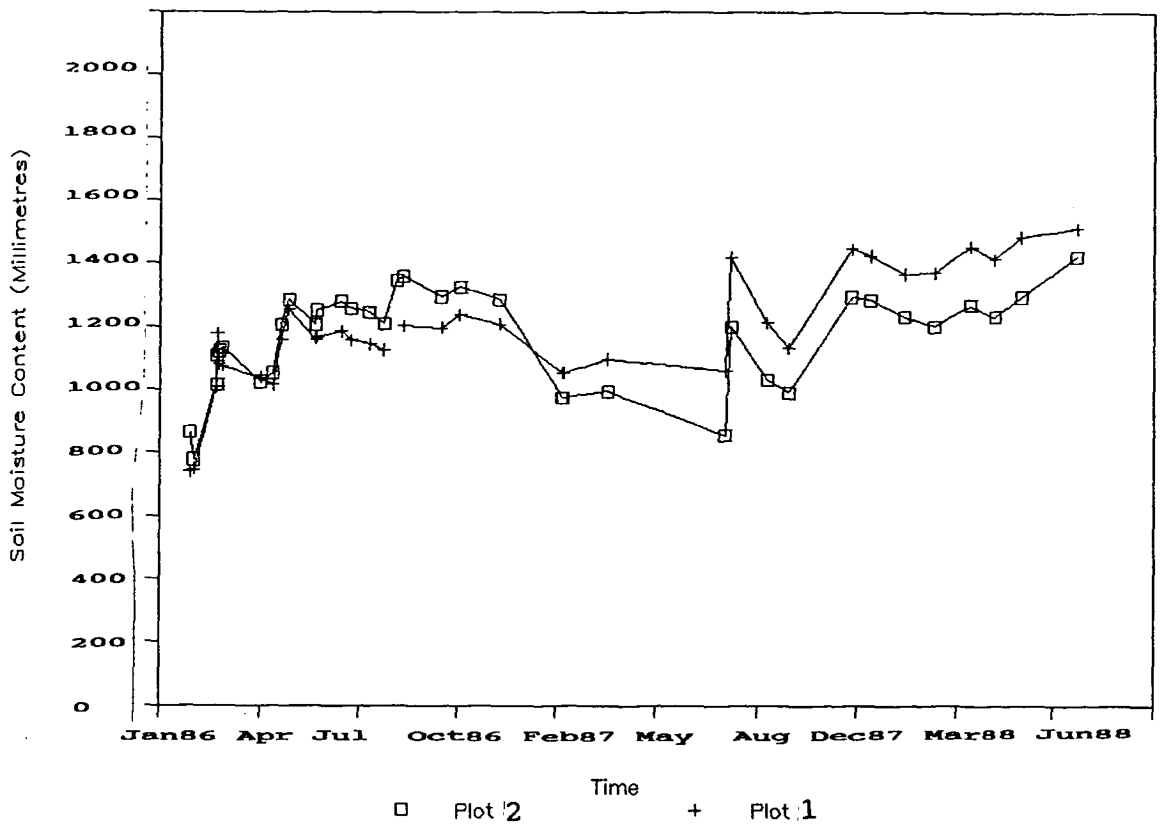


FIGURE 4.2 The Variation of Soil Moisture Content Cumulated with Depth to 3 Metres with Time, Plots 1 and 2

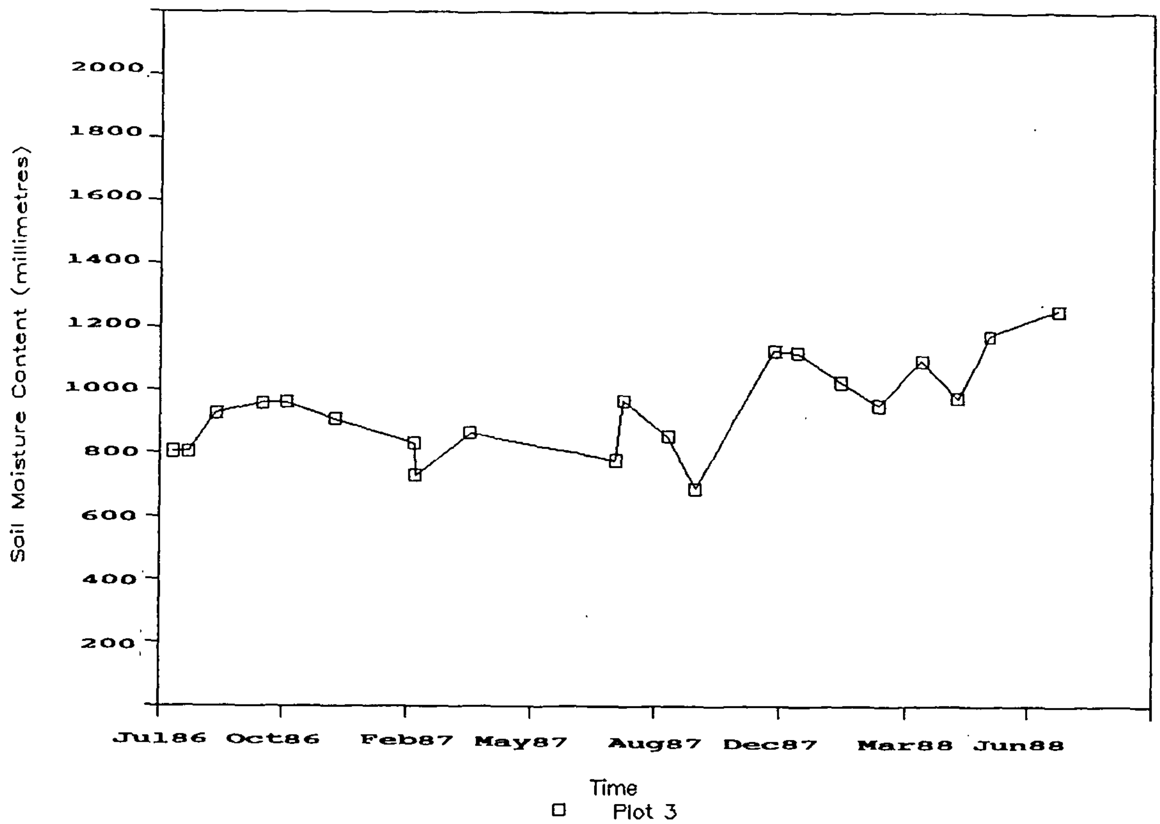


FIGURE 4.3 The Variation of Soil Moisture Content Cumulated with Depth to 3 metres with Time, Plot 3

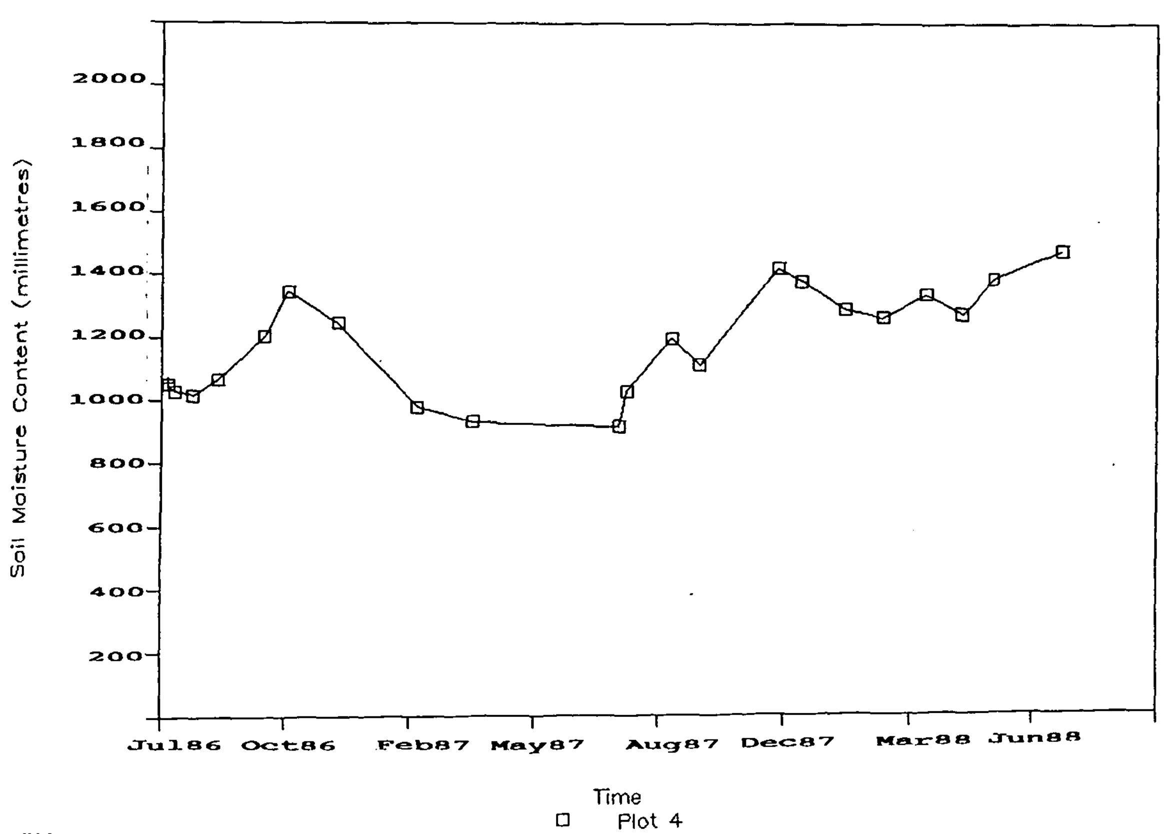


FIGURE 4.4 The Variation of Soil Moisture Content Cumulated with Depth to 3 metres with Time, Plot 4

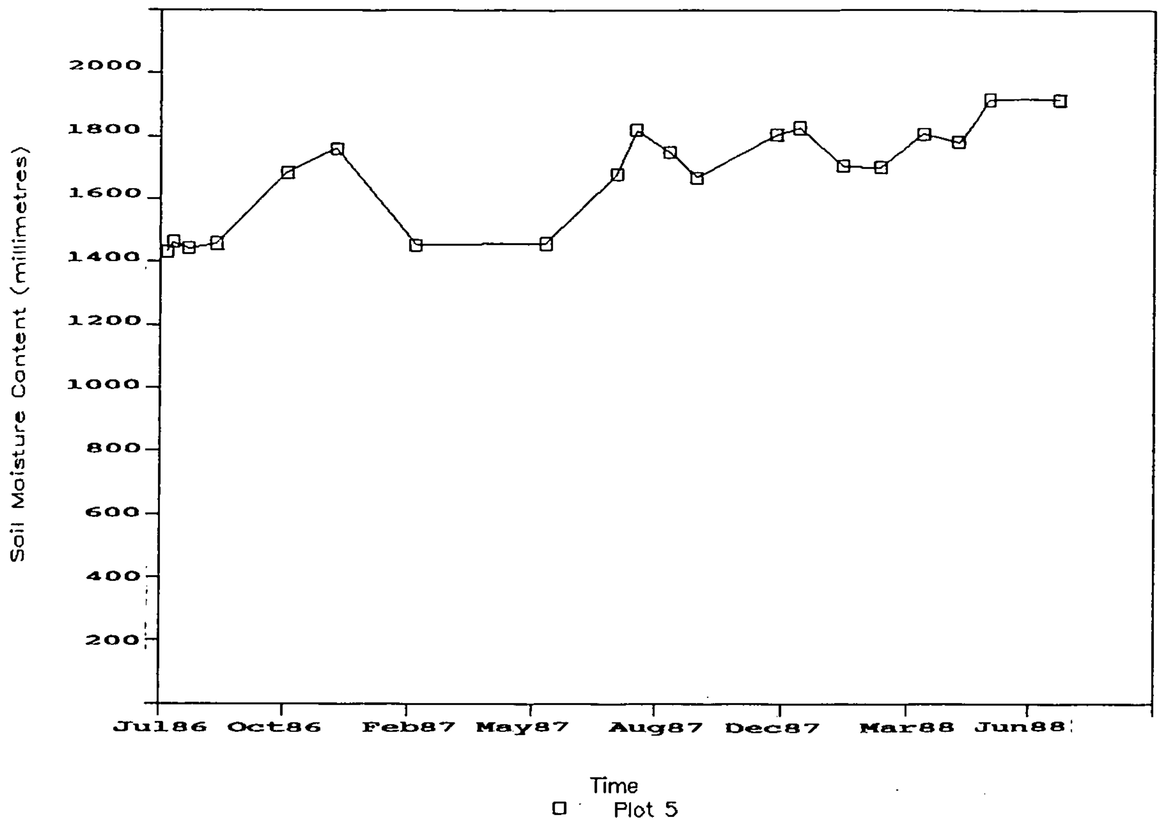


FIGURE 4.5 The Variation of Soil Moisture Content Cumulated with Depth to 3 metres with Time, Plot 5

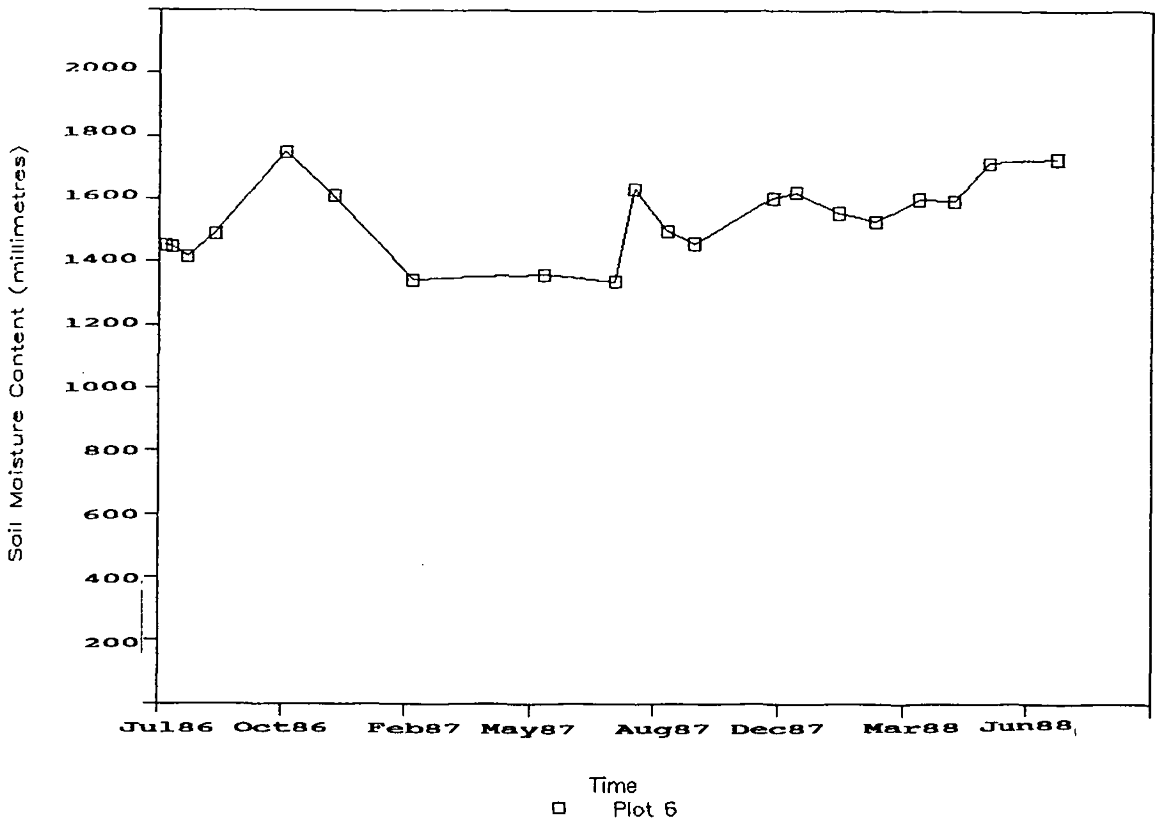


FIGURE 4.6 The Variation of Soil Moisture Content Cumulated with Depth to 3 metres with Time, Plot 6

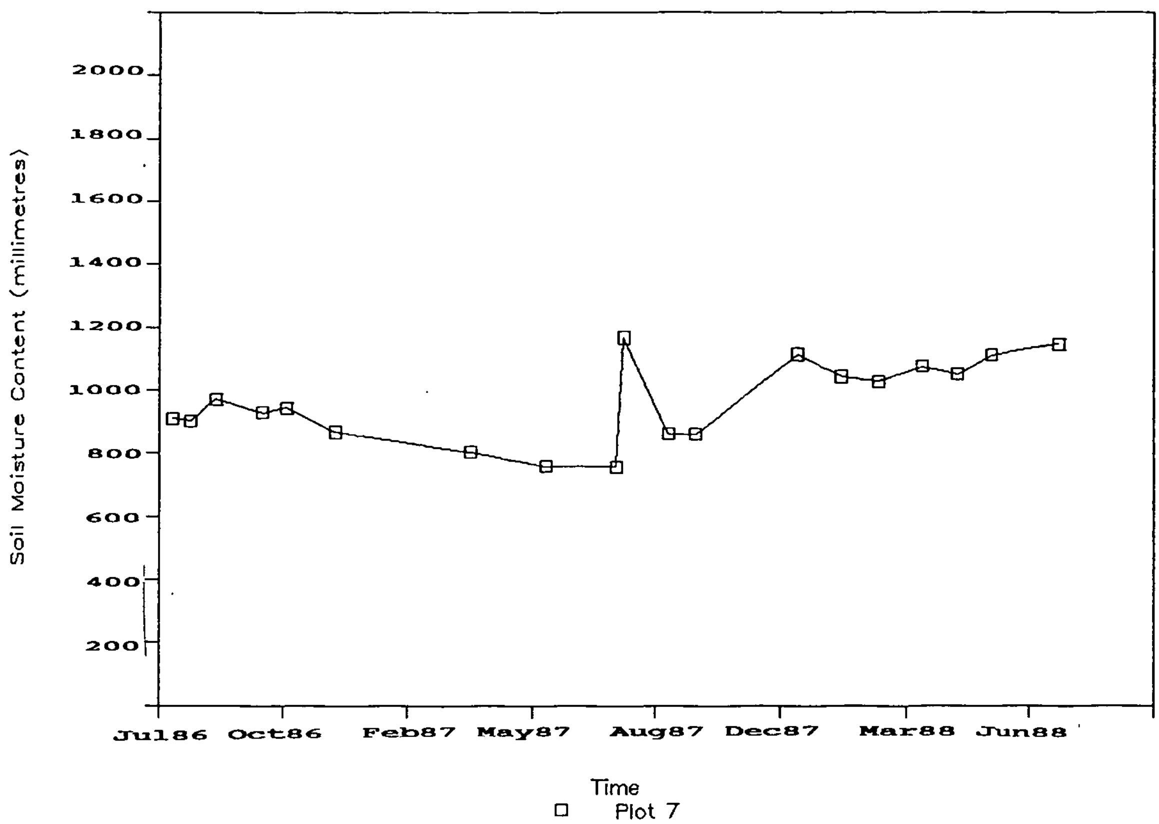


FIGURE 4.7 The Variation of Soil Moisture Content Cumulated with Depth to 3 metres with Time, Plot 7

A similar contrast in soil moisture content was observed between the mature vegetation in plot 7 and the pasture in plot 4. Plot 7 had a much lower soil moisture content due to the higher evapotranspiration rate.

The soil moisture contents of the study plots will be discussed further in the context of the modelling in Chapter 5.

4.2 Lysimeter Study

The experimental design for the waste dump leachate program incorporated two lysimeters to facilitate examination of water movement in the surface layers of the dump. These two lysimeters, known as plots 1 and 2, were located in the larger vegetated plot known as plot 4 and next to the runoff plot (plot 3). The lysimeters are described in Section 2.2.3. The materials used to fill the lysimeters are described in Section 4.5.

4.2.1 Data Collection

Data collected from the two lysimeters included soil moisture and drainage from the bottom of the lysimeters. The techniques for obtaining soil moisture storage were described above. During each site visit the leachate collection containers underneath the lysimeters were checked for drainage. The leachate volume was recorded and a sample sent to the University of Queensland for analysis. This information was essential for the verification of the water quality modelling.

4.2.2 Results and Discussion

Plot 1 first produced drainage before the 13/07/88 site visit. Somewhat over 100 litres were collected but this is not the total amount as the container was overflowing. Sixty litres were collected during the visit of 26/07/88.

No drainage was produced from plot 2 until 26/07/88 when 4 ml was collected. This is thought to be seepage between the edge of the claystone seal layer and the lysimeter wall because of an increase in the moisture content of the combusted shale and claystone layer because of heavy rain (202 millimetres) in June and early July. Drainage is not expected to increase or to continue, provided that claystone seal layer continues to seal and there are not extended periods of high precipitation.

4.3 Runoff Determination

A runoff plot (plot 3) was prepared. It was situated in the vegetated plot next to the lysimeters. The purpose of the runoff plot was to compare runoff with water infiltration in the lysimeters (plots 1 and 2). The design of the lysimeters allowed for 0.1 metre of ponding before runoff occurred.

4.3.1 Experimental Plot

The runoff plot was prepared by digging a hole 3.5 metres by 4.5 metres and 3 metres deep. Two neutron probe access tubes were installed and the hole was filled with a spent shale overburden mixture in a similar manner to the lysimeters. The top 0.1 metre was covered with topsoil and seeded in the same manner as the lysimeter and the rest of the vegetated plot around the lysimeters. The plot was contoured slightly (approximately 1 in 100), a mound placed around the top to deflect water running down from up slope of the plot, and guttering installed around the bottom with a pipe to a collection drum.

During the maintenance visits to the lysimeters site the volume in the runoff drum was recorded.

4.3.2 Results and Discussion

Table 4.2 presents the volume of runoff water collected and the runoff in terms of height in millimetres of water over an area.

In order for runoff to occur, the capacity of the soil to absorb incoming water (ie. for rain to soak into the surface) must be exceeded. So to interpret the runoff volumes it is useful to consider infiltration capacity.

Marshall (1985) quotes an infiltration threshold of 20 millimetres per rainfall event from a 5^{o} claystone surface, and corresponding thresholds of 90 millimetres per event for topsoil and 120 millimetres per event for spent shale. Rainfall events exceeding these thresholds would be expected to produce runoff. These values were averaged to determine the infiltration threshold for a 50% claystone, 50% spent shale mixture which was calculated to be about 65 millimetres per event. Initially the infiltration capacity of the topsoil would govern the infiltration rate of the runoff plot.

The relation between runoff and cumulative rainfall over the runoff accumulation period is shown in Figure 4.8. It is similar to Marshall's observations for topsoil, with an infiltration threshold of 60 millimetres. It should be noted that the experimental method in the present experiment differs from that of Marshall in that the slopes of the plots were not identical and the runoff volumes were collected more frequently in the earlier study.

TABLE 4.2 Volume of Runoff Water Collected from the Runoff Plot, Plot 3

DATE	RUNOFF VOLUME (litres)	RUNOFF DEPTH (millimetres)
2/09/86	63	4
9/10/86	11	1
29/10/86	62	4
7/12/86	32	2
10/02/87	22	1
11/03/87	60	4
27/03/87	10	1
30/04/87	95	6
13/05/87	4	0.5
26/05/87	5	0.5
22/06/87	10	1
28/07/87	20	1
2/09/87	45	3
22/10/87	45	3
26/11/87	200	13
15/12/87	12	1
19/01/88	10	1
17/02/88	25	2
24/03/88	160	10
21/04/88	10	1
18/05/88	101	6

No further data, due to change of operator

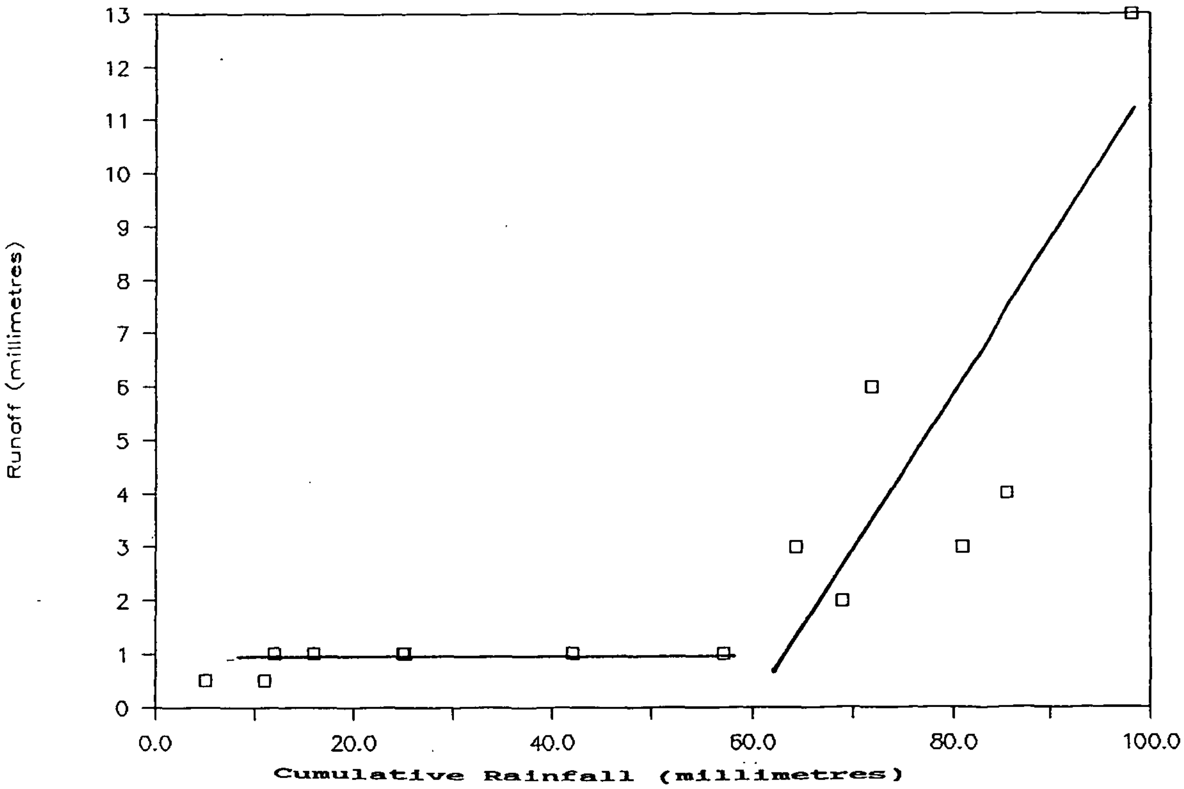


FIGURE 4.8 Rainfall Runoff Relationship for Plot 3

Infiltration depends on both the hydraulic conductivity and the hydraulic gradient prevailing in the soil surface zone (Hillel 1982). The hydraulic gradient may be affected by the conditions existing throughout the profile (including rainfall and infiltration). Thus variation of soil infiltrability, and hence runoff, depends on soil properties such as suction, texture, structure, uniformity and occurrence or otherwise of a surface crust as well as on the properties of the vegetation, ie complete or partial surface cover, and interception.

Runoff also depends of surface roughness. It is the portion of water supply to the surface which neither is absorbed by the soil nor accumulates on the surface (puddles) but runs down slope.

4.4 Meteorological Data

4.4.1 Data Collection

A weather station was installed next to the lysimeters. The weather station consists of a 30 metre tower with sensors as follows.

		Manufacturer
30 metre level:	Wind Direction	Weathermeasure
	Wind Speed	" "
	Propeller Anemometer (vertical wind fluctuations)	" "
	Temperature	" "
10 metre level:	Wind direction	" "
	Wind Speed	" "
	Temperature	" "
	Humidity	" "

1 metre or		
ground level	Wind Speed	" "
	Temperature	" "
	Tipping Bucket Rain Gauge	
	(data logged)	" "
	Tipping Bucket Rain Gauge	
	(chart recorder)	MRI
	Post Rain Gauge	Mitre 10
	Solar Radiation Sensor	Weathermeasure
	Evaporation Gauge	Geosource

The weather station was data logged on a continuous basis. Periodically the span of the instruments was reset to account for electronic drift. The data were calibrated using routines developed by the author for PARADOX software on an IBM personal computer.

4.4.2 Data summary

Precipitation and evaporation were the meteorological data of importance for this project and were the only results presented here.

The monthly rainfall for Rundle during the study period is shown in Figure 4.9. The Rundle data were from the Weathermeasure rain gauge except during periods when the data logger was known to be malfunctioning or being reset. During these periods data was supplemented by information from the chart recording rain gauge and the post rain gauge. The Gladstone meteorological data is from the bureau of meteorology, Gladstone office. Examination of the information shows that there is a variation in rainfall between Gladstone and Rundle which are about 30 kilometres

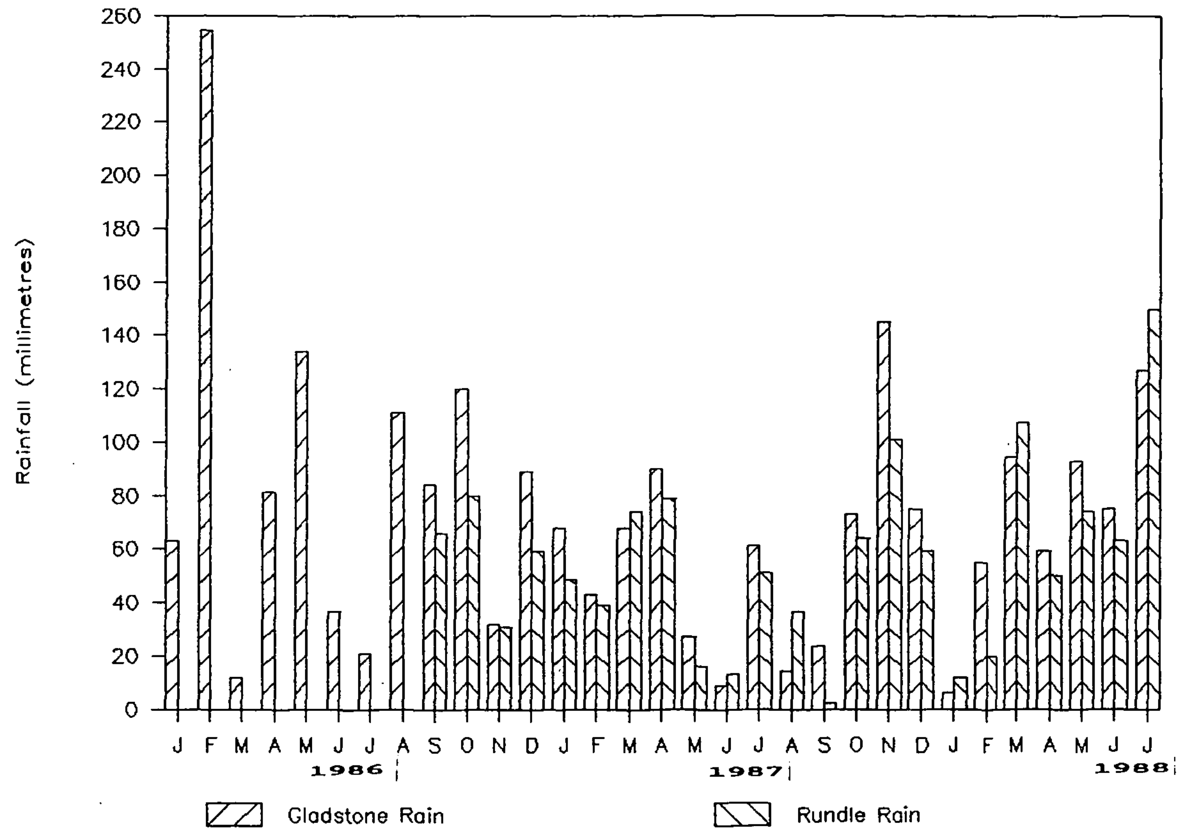


FIGURE 4.9 Comparison of Rainfall at Gladstone and Rundle, 1986 to 1988

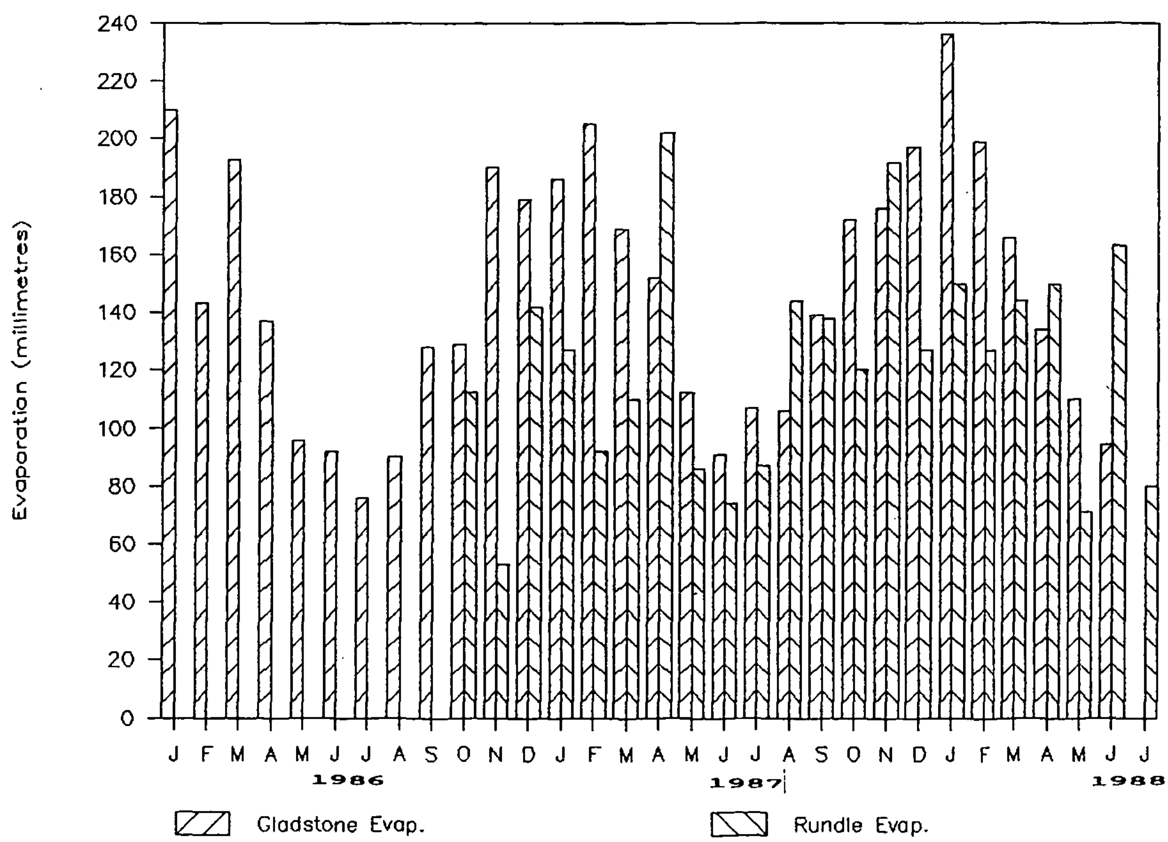


FIGURE 4.10 Comparison of Evaporation at Gladstone and Rundle, 1986 to 1988

apart. Rundle is usually drier than Gladstone. This confirms personal observations where it was common to experience heavy rain in Gladstone whilst little occurred on site, and vice versa.

Comparison with the long term average rainfall (see Table 4.3) accumulated over 108 years at Rockhampton (70 kilometres away) indicates that the seasons recorded during this study do not reflect long term trends in two ways. The seasonal nature of the long term rainfall (60% of the annual rain falling in the four months between December and March) was not observed during the study period. The rainfall was less than average during 1986 and 1987.

Monthly evaporation is presented for Rundle in Figure 4.10, and compared with the Gladstone evaporation data. Estimates for missing data from the Rundle meteorological station were based on the average of available data for that month. The observed Gladstone evaporation is generally higher than that recorded at Rundle. This was not expected, as Marshall (personal communication) indicated Gladstone evaporation data was used for earlier work at Rundle as evaporation was not expected to vary greatly over the distance between Gladstone and Rundle. The likely reason for variations in the pan evaporation records is slight physical differences in the evaporation pans. Slight variations, such as differences in the height above ground, surrounding terrain and ground cover have been shown to result in large differences in recorded pan evaporation (Eagleman 1967).

During 1987 Gladstone evaporation was greater than the 16 year Rockhampton average and Rundle evaporation was less than the 16 year average (Table 4.4).

TABLE 4.3 Rainfall Data (Gladstone 1986 to 1988, Rundle 1986 to 1988, and, Rockhampton 108 year average) (Rainfall in millimetres)

MONTH	GLADSTONE	RUNDLE	ROCKHAMPTON (108 year)
Jan 86	63		185
Feb 86	255		185
Mar 86	12		125
Apr 86	81		55
May 86	134		50
Jun 86	37		60
Jul 86	21		45
Aug 86	111		25
Sep 86	84	66	30
Oct 86	120	80	55
Nov 86	32	31	75
Dec 86	89	59	125
Jan 87	68	49	
Feb 87	43	39	
Mar 87	68	74	
Apr 87	90	79	
May 87	27	16	
Jun 87	9	13	
Jul 87	61	51	
Aug 87	14	37	
Sep 87	24	2	
Oct 87	73	64	
Nov 87	145	101	
Dec 87	75	59	
Jan 88	6	12	
Feb 88	55	27	
Mar 88	94	107	
Apr 88	59	50	
May 88	93	74	
Jun 88	75	63	
Jul 88	127	150	

TABLE 4.4 Evaporation Data (Gladstone 1986 to 1988, Rundle 1986 to 1988, and, Rockhampton 16 year average) (Evaporation in millimetres)

MONTH	GLADSTONE	RUNDLE	ROCKHAMPTON (16 year)
Jan 86	210		100
Feb 86	143		165
Mar 86	193		160
Apr 86	137		140
May 86	96		110
Jun 86	92		95
Jul 86	76		100
Aug 86	90		110
Sep 86	128		135
Oct 86	129	112	175
Nov 86	190	53	185
Dec 86	179	142	200
Jan 87	186	127	
Feb 87	205	92	
Mar 87	169	110	
Apr 87	152	202	
May 87	112	86	
Jun 87	91	74	
Jul 87	107	87	
Aug 87	106	144	
Sep 87	139	138	
Oct 87	172	120	
Nov 87	176	192	
Dec 87	197	127	
Jan 88	236	150	
Feb 88	199	127	
Mar 88	166	144	
Apr 88	134	150	
May 88	110	71	
Jun 88	94	163	
Jul 88		80	

4.5 Material Characterisation

4.5.1 Results

Plots 1,2, and 3 comprise 50% overburden and 50% spent shale mixture overlain by a 10 centimetre layer of topsoil. A 1 metre compacted claystone layer was placed in the bottom of plot 2. A detailed chemical analysis of a sample of the spent shale and overburden is presented in Appendix 2.

The overburden used in plots 1, 2, and 3 is likely to be similar to the undisturbed soil profiles of plots 4, 5, 6, and 7. An indication (Table 4.5) of the most important physical and chemical properties of the overburden was obtained from the results presented by Marshall and Johns (1982). Their data for topsoil and spent shale is also quoted. Table 4.6 presents the size analysis of the spent shale used in these studies. These analyses are only an indication of the approximate properties of the materials used in the present study based on previous experience of the materials used, not the measured properties. These properties of a representative sample of the particular materials vary extensively with depth and geographic location.

TABLE 4.5 Physical and Chemical Properties of Topsoil, Spent Shale and Overburden

	Topsoil	Spent Shale	Overburden
pH	5.8	9.3	5.0
Organic Carbon %	1.7	2.0	0.6
Total Nitrogen %	0.1	0.5	0.5
Phosphorus ppm	13	50	9
Cation Exchange Capacity me/100g	43	33	56
Exchangeable Sodium ppm	486	541	2238
Chloride ppm	196	374	2583
Course + fine sand %	29	-	14
Silt + clay %	71	-	86
Diffusivity mm/hr	105	141	0.7

(After Marshall 1985)

TABLE 4.6 Size Analysis of Spent Shale

Size Fraction (mm)	Mass %
-2.8 +2.0	18.1
-2.0 +1.0	30.8
-1.000 +0.500	17.9
-0.500 +0.250	12.3
-0.250 +0.125	8.1
-0.125 +0.075	8.3
-0.075 +0	4.5

(After Cutler 1986)

4.6 Leaf Area Index

Leaf Area Index (LAI) is leaf area per unit area of land. It is important for plant growth studies, physiological studies on whole plants, and for plant evaporation studies, (Marshall 1968, Palit and Bhattacharyya 1984, Rose 1984). However, as Rose (1984) pointed out, most available methods are labour intensive, many involve a high degree of operator skill, some involve destructive sampling and many are only suitable for either forests or pastures and crops.

4.6.1 Selection of Method

A wide variety of techniques for determining Leaf Area Index is quoted in the literature. Using the categories developed by Marshall (1968) available methods of LAI determination were reviewed.

Methods requiring destructive sampling were originally laboratory methods, hence the leaves were removed to the laboratory before measuring their area. These methods are listed below.

(a) Direct methods
(These include all the techniques used to calibrate other techniques.)

- Graph paper method: a leaf is outlined on graph paper or a grid, the number of squares are counted within the outline.
- Planimetric method: an outline of the leaf is obtained and measured using a planimeter.
- Electronic leaf area meter: leaves are passed through and the area determined automatically.

(b) Methods dependent on the leaf area relationship:

- Whole leaf methods: these make use of the relatively consistent relationship between leaf area, and weight, either fresh or dry weight, in determining leaf area. The area of a sample of leaves is determined, the leaves are weighed, or alternatively dried and weighed, and the relationship between leaf area and weight determined. Repeated leaf weighings can be converted to leaf area using the established relationship. Inaccuracies arise as the relationship varies with plant growth and environmental conditions.
- Sub-sampling methods: these use parts of leaves in a similar manner to that described above.

Non-destructive methods, originally developed for field use, include:

(a) Comparative methods using leaf shapes and geometric shapes.

- Method of standards using actual leaf images.
- Method of standards using simple shapes.

(b) Visual method.

- Visual estimation of leaf area is a method suitable for forests developed by Carbon et al. (1979a). The estimates may be corrected against harvested and measured standards. The method relies on operator training and experience.

(c) Methods based on the probability of light penetration through foliage.

- Point quadrat analysis (Warren Wilson 1959).
- Fisheye photographs (Anderson 1981).
- Transmittance of the sun's beam, as developed by Lang (1987b).

The method developed by Lang was selected as it was suitable for both forests and pasture, non-destructive, did not require subsampling (a tedious process in forests), required no operator training, appeared to be well developed and tested, and was the only technique that was being developed for commercial application. In fact, the last of the prototypes and the first commercial model were hired to use for data collection for this project.

The method is developed in Lang et al. (1985), Lang and Xiang (1986), Lang (1986), and Lang (1987b). Lang and Miller at CSIRO, Division of Environmental Mechanics, have developed an instrument for obtaining LAI from transmittance of sunbeams which is known as the DEMON leaf area instrument (Lang and Miller 1987).

4.6.2 Equipment and Method

The DEMON consists of a sensor and the instrument which includes a micro computer monitor. The sensor is made up of (Lang et al. 1985):

- a silicon photo cell (the detector),
- a 430nm filter (leaves have less than 5% transmission and reflectance at this wavelength and thus will appear black to the detector,
- a collimating tube in order to obtain a distinct beam instead of diffuse light, and
- a sight using a shadow cast by the sun, so that it can be pointed directly at the sun.

The instrument was designed to measure the light energy of the direct beam of the sun and average these energies in a prescribed way over a period of 34 seconds (Lang and Miller 1987).

Essentially it calculates the projected areas of leaves and other parts of the canopy from measurements of the penetration of the direct beam of the sun through the foliage. Leaf area is related to the logarithm of the transmittance (transmittance is the ratio of measurements of light in the vegetation to those in unprotected sun at practically the same time). To do this a series of traverses are required with the sun at different angles to the vertical. For discontinuous canopies the leaf area obtained will be more accurate if the logarithm of transmittances is averaged over short intervals which are averaged over the full length of the traverse.

4.6.3 Experimental Method

For the purposes of Leaf Area Index determination plots 2, 3, and 4 were treated as a single plot because of the small size of plots 2 and 3, and the uniformity of the vegetation between the plots. This was known as plot 2-3-4. The Leaf Area Index of plots 5, 6, and 7 were each determined separately. Plot 1 was not included in the LAI determination as it contained no vegetation.

During the averaging period the instrument was carried on foot through plots 6 and 7 along a traverse, typically about 20 metres long. The area traversed extended beyond the plots used for the vegetation survey described below as the vegetation appeared fairly uniform. The quantity of ground level grasses in both plots 6 and 7 was very limited. In order to facilitate ease of measurement they were not included.

Determination of the Leaf Area Index of the low vegetation in plots 2, 3, and 4 and the mixed vegetation in plot 5 would have been easier if rails were installed so that the detector could be driven along the rails. However, rails should have been installed when the area was seeded. The alternative of fixing the sensor to a broom handle so that it could easily moved along at ground level was found to be satisfactory.

Between 20 and 40 measurements were taken at a variety of sun angles for each plot. The measurements were downloaded from the DEMON to an IBM personal computer for processing with the software, DEMSOFT1, developed to process the data from the DEMON to produce Leaf Area Index for each plot (Lang 1987a). Erroneous data points resulting from clouds interrupting the sun's beam, and swatting sand flies and mosquitoes were deleted prior to processing.

Leaf Area Index was determined for the prescribed plots on December 6, 1987, February 15, 1988 and July 1, 1988.

4.6.4 Results and Discussion

The results obtained are presented in Table 4.7.

Visual comparison of the vegetation in the plots confirms that the plot 2-3-4 would be expected to have a higher Leaf Area Index than plots 5, 6, or 7. Eucalypts are generally understood to have a lower Leaf Area Index than other forms of vegetation. Leaf Area Index of 0.8 to 2.9 has been reported for eucalypt forest in the literature (Carbon et al. 1979a, Carbon et al. 1979b, Anderson 1981, Pook 1984). It has also been noted that the value for regrowth forest may equal that of the original forest within 5 years (Carbon et al. 1979b, and, Carbon et al. 1981) and has been reported as exceeding that of the original forest. The Leaf Area Index determined for plots 5 and 6 (2.1 to 2.7), compared with plot 7 , the original vegetation (1.8 to 2.3), reflects this.

TABLE 4.7 Leaf Area Index for the Vegetated Plots

PLOT	DATE	LAI	sd
2-3-4	06/12/87	3.9	0.2
	15/02/88	4.6	0.3
	01/07/88	3.9	0.3
5	06/12/87	2.2	0.2
	15/02/88	2.1	0.5
	01/07/88	2.5	0.5
6	06/12/87	2.1	0.2
	15/02/88	2.7	0.4
	01/07/88	2.1	0.4
7	06/12/87	1.8	0.1
	15/02/88	2.3	0.5
	01/07/88	2.0	0.6

All plots show a seasonal variation in Leaf Area Index. The variation observed for plot 7 closely matches the seasonal variation for eucalypts of 0.45 reported by Pook (1984). This is less than the variation that has been reported for pastures, crops and deciduous forests. Plot 2-3-4, pasture, shows a greater variation. All plots show an increase in Leaf Area Index between the December and February determination, probably corresponding with summer growth. Leaf Area Index then drops back to about the December level (more or less) for all plots except plot 5. This is probably related to water availability during the middle of the year. Plot 5 is located close to a farm dam which may mask the effect of a reduction in water availability on Leaf Area Index.

The standard deviation observed during this study was marginally higher than that reported by Anderson (1981).

4.7 Vegetation Survey

The vegetated plots were located in areas that meet the overall project objectives, that is, in existing areas containing vegetation types needed by the project. The major plots are the vegetated area surrounding the lysimeters (2-3-4), 2 areas of intermediate aged vegetation (plots 5 and 6) an a convenient area of mature vegetation typical of the Rundle area (plot 7).

5.7.1 Survey Method

A survey of all the vegetated plots was carried out in August 1987. The objectives were to collect data to characterise the sample plots and to provide a reference for the water uptake measurements. The 1987 survey used circular plots of 1000 square metres (the radius of the circle was 17.6 metres) centred on a neutron probe tube (or at the edge of the lysimeter trench lid for plot 2-3-4).

A smaller survey was carried out in July 1986. Plots 2 and 3 were surveyed separately, and surveys over smaller areas within plots 5 and 6 were carried out. In addition, plots 2 and 3 were surveyed separately in August 1987.

The species present were identified with the help of the Queensland herbarium, with the number of individuals of each species was recorded. Each species was classified according to the type of plant (grass, herb, tree, shrub) and an assessment was made of the per cent cover (McDonald et al. 1984).

4.7.2 Results and discussion

The results are presented in tables 4.8 to 4.13. Due to the periodic nature of the site visits it was not possible to collect sufficient samples of fertile material to identify the eucalyptus species present. Thus there is insufficient information to perform a statistical analysis in order to compare the sample plots with the results from the earlier research into the vegetation at the Rundle site (Burgman and Thompson 1981a, Marshall et al. 1985).

Comparison of plots 5 and 6 between 1986 and 1987 is also difficult because of the different size survey areas. Plots 2 and 3 show an increase in cover between 1986 and 1987, but a decrease in species diversity with increases in the dominant species **Chloris gayana** associated with a reduction in the numbers of species of annual herbs.

TABLE 4.8 Vegetation Survey:
Plot 2, July 1986 and August 1987

PLOT 2 DATE: July 1986

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	++	5
2	**Stylosanthes humilis**	H	5	<< 1
3	Annual herb species	H	12	<< 1

PLOT 2 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	+++	> 90
2	**Stylosanthes humilis**	H	5	<< 0.1

Where number of individuals could not easily be determined an indicator was used:

++++ very many
+++ many
++ some
+ few

TABLE 4.9 Vegetation Survey:
Plot 3, July 1986 and August 1987

PLOT 3 DATE: July 1986

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Rhynchelytrum repens**	G	++	1
2	**Cenchrus echinatus**	G	++	1
3	**Bothriochloa decipiens**	G	++	1
4	**Malvaceae sp.**	H	+	< 1
5	**Euphorbia hirta**	H	+	< 1
6	**Tridax procumbens**	H	+	< 1
7	**Glycine tomentella**	H	+	< 1

(Very poor growth from the seeding, essentially bare soil with a few annual herb species.)

PLOT 3 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	++++	10
2	**Stylosanthes humilis**	H	+	<< 1
3	**Fitzroy** "cootch"	G	++++	10
4	**Verbena tenuisecta**	H	++	5-10
5	**Stachytarpheta jamaicensis**	H	++	5-10
	Bare Soil			50

TABLE 4.10 Vegetation Survey:
Plot 2-3-4, August 1987

PLOT 2-3-4 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	++++	54
2	**Stylosanthes humilis**	H	+	1
3	**Fitzroy** "cootch" & others	G	++++	5
4	**Verbena tenuisecta**	H	++	3
5	**Stachytarpheta jamaicensis**	H	++	3
6	**Acacia sp** <1m height	S	20	< 1
7	**Eucalyptus citriodora**	T	1	<< 1
	Bare Soil			34

TABLE 4.11 Vegetation Survey:
Plot 5, July 1986 and August 1987

PLOT 5 DATE: July 1986

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	+++	80
2	**Acacia Leiocalyx**	S	++	10
3	Native Grass sp.	G	++	< 1

Plot 5 consisted of three squares of 1 m^2 area for the 1986 survey.

PLOT 5 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	**Chloris gayana**	G	+++	38
2	**Acacia Leiocalyx**	T	81	10
3	**Melaleuca sp. poss M. nervosa**	T	7	< 1
4	**Coelospermum reticulatum**	S	55	2
5	**Eucalyptus alba**	T	1	< 1
6	**Sesbania cannabina**	S	4	< 1
7	**Eucalyptus sp.** poss **E. tereticornis**	T	1	<< 1
	Bare Soil			50

Plot 5 survey area was a rectangle 22m by 44m due to the proximity of a dam and a fenceline.

TABLE 4.12 Vegetation Survey:
Plot 6, July 1986 and August 1987

PLOT 6 DATE: July 1986

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	Very dry short grass cover	G	+++	30
2	**Acacia Aulacocarpa**	T	2	2
3	**Acacia Leiocalyx**	S	4	12
4	**Melaleuca nervosa**	T	4	4
6	**Coelospermum reticulatum**	S	++	< 1
8	**Jacksonia scoparia**	S	6	10
9	**Petalostigma pubescens**	S	1	< 1
10	**Eucalyptus sp.** 1	T	3	8
11	**Eucalyptus sp.** 2	T	1	< 1
12	**Eucalyptus sp.** 3	T	1	< 1

Plot 6 was a 4m by 4m rectangle for the 1986 survey.

PLOT 6 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	Very dry short grass cover	G	+++	20
2	**Acacia Aulacocarpa**	T	22	4
3	**Acacia Leiocalyx**	S	202	15
4	**Melaleuca nervosa**	T	10	1
5	**Melaleuca argentea**	S	95	9
6	**Melaleuca sp.**	S	++	< 1
7	**Coelospermum reticulatum**	S	18	< 1
8	**Jacksonia scoparia**	S	12	1
9	**Petalostigma pubescens**	S	16	1
10	**Eucalyptus sp.** 1	T	20	3
11	**Eucalyptus sp.** 2	T	1	<< 1
12	**Eucalyptus sp.** 3	T	3	< 1
13	**Eucalyptus sp.** 4	T	5	2

Table 4.13 Vegetation Survey:
Plot 7, August 1987

PLOT 7 DATE: August 1987

Sp. No.	SPECIES	TYPE	No Ind.	% COVER
1	Very dry short grass cover	G	+++	<10
2	**Acacia Aulacocarpa**	S	72	3
3	**Acacia crassa subsp.longicoma**	S	7	1
4	**Eucalyptus crebra**	T	19	22
5	Unidentified sp.	S	2	1
6	**Lantana sp.**	S	++	< 1

Overall, the sample plots appear to have lower species diversity than would be expected from the work of Marshall et al. (1985), or from the original Rundle vegetation survey (Burgman and Thompson 1981a). Marshall et al. (1985) found that four Rundle plant communities on undisturbed sites contained between 42 and 55 species in an area of 1042 square metres. They found that the vegetated plots sown with a pasture and native seed mixture similar to that used in plots 1, 2, 3 and 4 in this study, with a topsoil layer over the surface resulted in approximately 5 or 6 species in an area of approximately 4 square metres, which extrapolated to 20 to 30 species in an area of 1042 square metres.

The most likely reason for the lower species diversity observed in the present study is that species diversity and comparative species diversity were key indicators of the relative performance of the various rehabilitation strategies that they tried. Thus the personnel working on the project were skilled at identifying species and focused attention on this. In contrast, the species composition of the current study plots was a relatively minor element in the overall study. Accordingly it was not the subject of extensive work.

5. MODEL PREDICTIONS AND INTERPRETATION

5.1 Short Term Modeling Predictions, Verification and Interpretation

The model verification process involved three stages: (i) model development, (ii) use of the model to make predictions, and (iii) verification using field data not used by the model to make these predictions. The validated model could then be used to make predictions of future events that are unable to be tested in the time frame of the project. This section deals with the model verification process. Model application to long term predictions is discussed in Section 5.2.

Seven series of model runs were performed. Each series represented one of the seven vegetated plots. Input rainfall and evaporation were from the Rundle meteorological station described in Section 4.4. To test the validity of the model two alternative strategies were used, ensuring that only part of the field data was used to calibrate the model and make initial predictions. The rest of the data would then be available to independently test these predictions.

The first model verification strategy involved using a portion of the available data (for example, the first six months of data) to test the model, determine the potential evapotranspiration coefficient and test the value selected for the soil factor. These values were used as model inputs when the model was run with the remaining rainfall and evaporation data. The predictions of soil moisture content produced by the model were then compared with the measured values from the field data over this period. If the two sets of values corresponded well the data was said to have verified the model predictions.

The second technique of model verification was between plots. The knowledge gained through running the model on one plot was used to determine the evaporation coefficients for another plot. In these cases the second plot included different conditions (such as soil properties, vegetation and initial soil moisture content) from the first. If the model results compared well with the measured soil moisture contents the model was said to have been verified by the field data.

The verified model parameters listed in Table 5.1 were used as inputs for the predictive modelling performed on long term average rainfall and evaporation, described in Section 5.2.

TABLE 5.1 Parameters Used as Inputs to WATBAL for Model Verification

Plot	1	2	3	4	5	6	7
Initial Soil Mois. (mm)	755	810	806	1214	1633	1453	910
Max Soil Mois. (mm)	1500	1500	1500	1500	1910	1750	1500
Soil Index	3.5	3.5	6.0	1.5	1.5	1.5	1.5
Start Date	Jan 21 1986	Jan 21 1986	Jul 27 1986	Jul 27 1986	Jul 27 1986	Jul 27 1986	Jul 27 1986
Pot. ET Coef:							
1986 Jan-Jun	0.34	0.34	-	-	-	-	-
1986 Jul-Sep	0.34	0.37	0.34	0.37	0.45	0.52	0.55
1986 Sep-Dec	0.34	0.47	0.34	0.47	0.45	0.52	0.55
1987 Jan-Jun	0.34	0.45	0.36	0.45	0.45	0.52	0.55
1987 Jul-Dec	0.34	0.45	0.38	0.45	0.45	0.52	0.34
1988 Jan-Jul	0.34	0.45	0.40	0.45	0.45	0.52	0.34

A sample of the model output is shown in Appendix 3 The output was in the form of a balance sheet. Column 1 gives the week number for that year (WK). The weekly pan evaporation is given in column 2 (EVAP). Column 3 gives the actual evapotranspiration coefficient (CF) used in the calculation of actual water demand. This was calculated from the formulas given in Section 3.4. The actual water demand for the week (ET) is given in column 4, calculated as the product of (EVAP) * (CF) * (PEC), where PEC was the Potential Evapotranspiration Coefficient entered by the user. The weekly precipitation is given in column 5. Column 6 or 7 gives the surplus (+) or deficit (-) of water inputs and outputs for the week. Deficits are only calculated until soil moisture storage is fully depleted (equal to zero). Column 8 (C-) accumulates column 7. The estimated soil moisture storage (ST) is shown in column 9. Column 10 gives an estimate of drainage (++), and is the water surplus over storage requirements. Column 10 is accumulated in column 11 (C++). The percentage level of soil moisture storage to maximum soil moisture storage (field capacity) is given in column 12 (RST).

The key parameters for model verification obtained from the model output were the soil moisture content in column 9 and the drainage, or infiltration beyond the root zone, in column 10.

The model runs for each of the seven vegetated plots were developed sequentially, and will be discussed in turn below. All soil moisture contents were at 3 metres depth.

Plot 1 was the unvegetated lysimeter. A maximum soil moisture content, for the top 3 meters, of 1500 millimetres was determined from the field capacity of the materials used in this lysimeter. This maximum soil water content was used for the modelling of plots 2, 3, 4 and 7. A soil index of 3.5 and potential evapotranspiration coefficient of 0.34 were found to give an acceptable (within 10%) correspondence of predicted and measured values of soil moisture for the period from January to June 1986 (Figure 5.1). These coefficients were used to run the model from June 1986 to July 1988.

During the first half of 1987 the correlation between predicted and measured water contents was poorer with the predicted values being approximately 20% greater than the field measurements. This difference between observed and measured values was also noted in the results from plots 2, 4, 5, 6 and 7 during this period. The occurrence of poor correlations between model and field results in all but one of the plots during this period, and the frequency of neutron probe malfunctions and repairs suggests that the problem may have been with the neutron probe. During one of the series of repairs the detector sensitivity may have been affected and remedied in a later series of repairs. The limited number of neutron probe determinations during this period was a result of the frequent repairs.

An alternative explanation for the variability of the results during this period could be that significant drying in the plots took place which was not predicted by the model. This points to a weakness in the model. The close correspondence of the predicted and measured values prior to the neutron probe repairs in January 1987 and subsequent to those in July 1987 lends weight to the suggestion that it may be a result of a neutron probe malfunction. This explanation has been supported by L. Connell in his work on the hydrological model for the entire dump. His work involved interpretation of the neutron probe data for all eight Rundle lysimeters. He has made the same observation for the data collected over the period in question (L. Connell, personal communication).

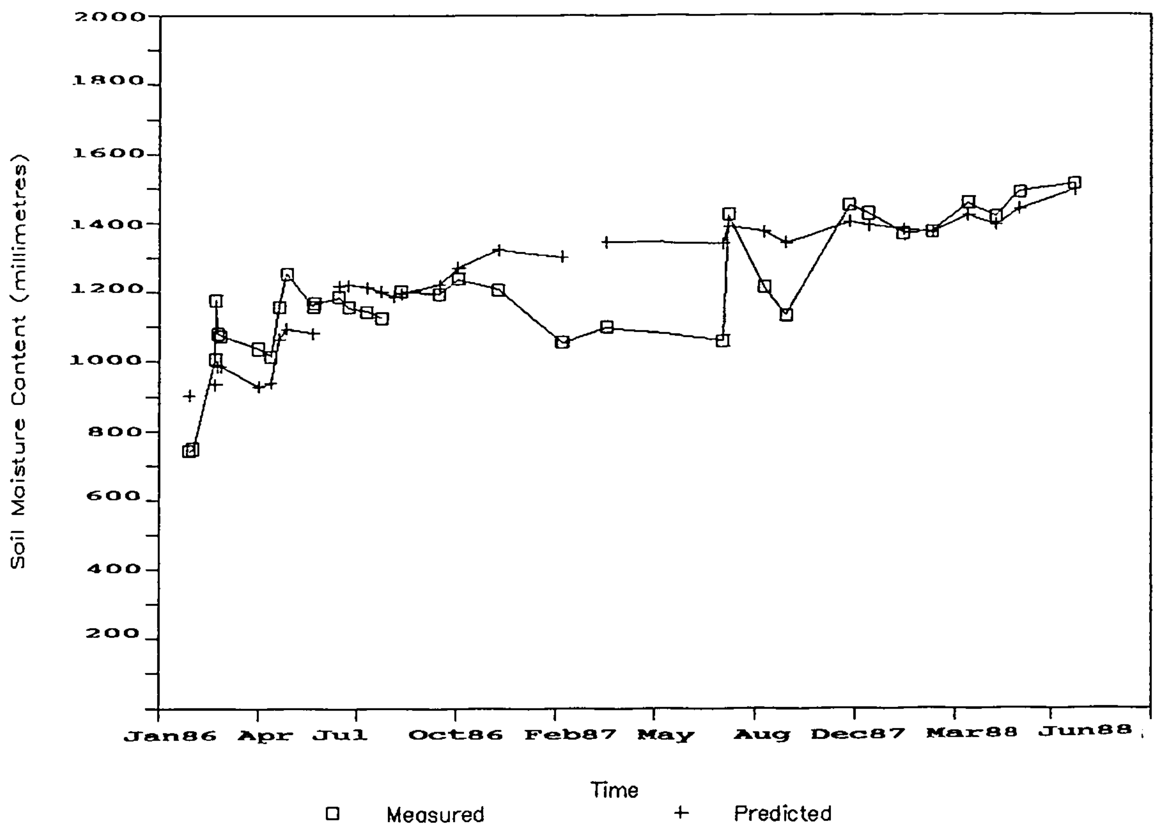


FIGURE 5.1 Measured and Predicted Soil Moisture Content, Plot 1

The second element of the model verification involved prediction of drainage or infiltration beyond the root zone. The model predicted that 162 litres of drainage would be produced from plot 1 in the week starting July 3, 1988. A quantity of drainage, approximately 100 litres or more, was produced between the site visit in May 1988 and the visit of July 13, 1988. A further 60 litres were collected between July 13 and the next site visit on July 26, 1988. The quantity of drainage produced conforms closely to predictions. The relative flow of leachate, all in a single week from model predictions, and over three weeks, observed in the field confirms the leachate flow model described in Section 3.3 for WATBAL and the field situation.

The soil index required for plot 2, the vegetated lysimeter, should be the same as the soil index of 3.5 used for plot 1. The same material was used in both of these plots. The potential evapotranspiration coefficient that applied to the bare soil of plot 1 should also be applicable to plot 2 for January 1986 to June 1986 prior to the growth of vegetation. Plot 2, and also plots 3 and 4, were seeded in May 1986. The information gained from the vegetation survey carried out in July 1986 and July 1987 was used to estimate potential evapotranspiration coefficients (which ranged from 0.37 to 0.47) for the remainder of 1986. The model was run and soil moisture contents determined for this period. These corresponded to within 10% with the measured values obtained from the field studies during 1986 (Figure 5.2).

The next step was to determine, from the 1986 run, the potential evapotranspiration coefficient applicable to 1987 and 1988. Field observations of plot 2 showed that by December 1986 dead vegetation had begun to accumulate on the soil surface. This dead vegetation would be expected to reduce evaporation slightly. The potential

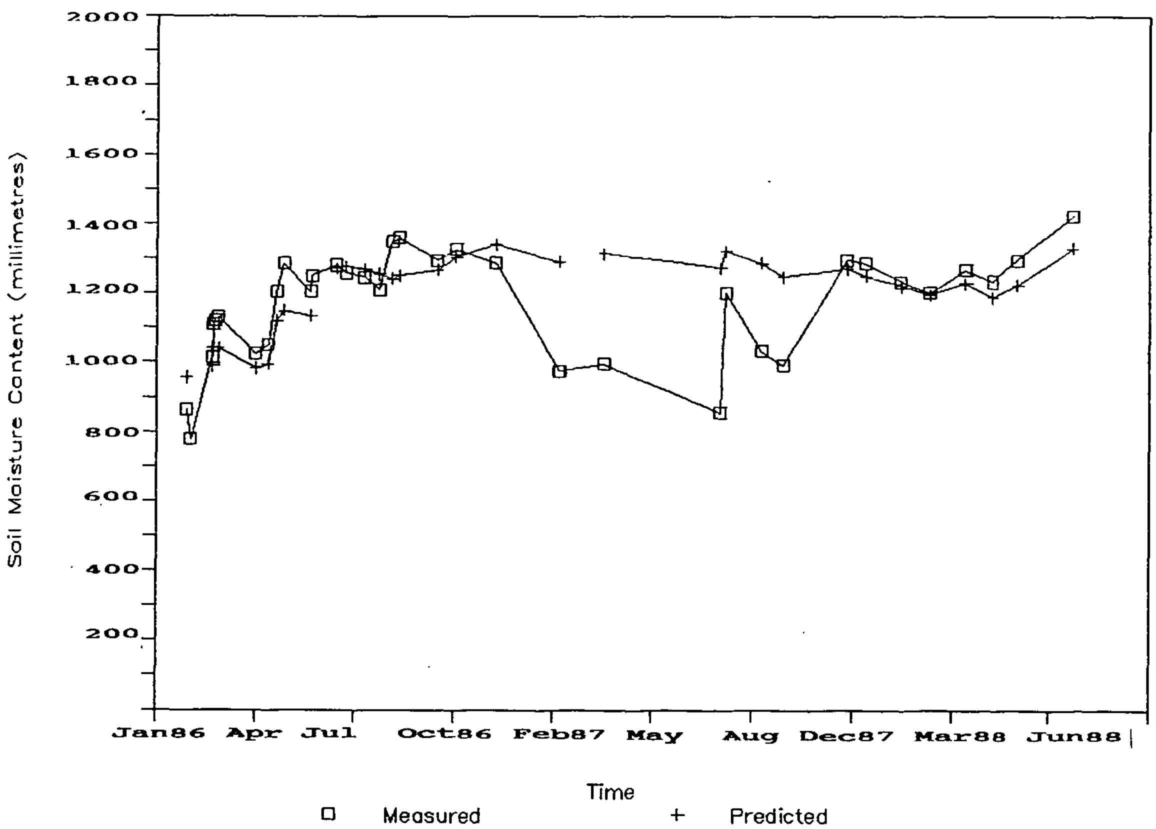


FIGURE 5.2 Measured and Predicted Soil Moisture Content, Plot 2

evapotranspiration coefficient that was used in the last quarter of 1986 was reduced by a small amount to reflect the proportion of dead vegetation. About 2% of the vegetation was dead so the coefficient was reduced by 0.02. The model was used to predict the soil moisture contents for 1987 and 1988. Comparison of these predictions with measured values indicated poorer correlation for the first half of 1987 and good (within 5%) correspondence for the remainder of the period. Suggested reasons for the discrepancy observed during 1987 were discussed above with respect to plot 1.

The model predicted no formation of drainage. This was verified by the field studies. For most of the study period observed data verified model predictions.

The model confirms the hypothesis that the difference in soil moisture content between plot 1 and plot 2 is due to the effect of vegetation growing on plot 2. This is represented by the higher potential evapotranspiration coefficient used for the model of plot 2. The model also attributed the absence of drainage from plot 2 entirely to the presence of vegetation. This was a simplification as the model does not account for the presence of the claystone seal layer associated with plot 2 on the potential for drainage from the lysimeter. If the claystone seal layer was the reason for zero drainage produced from plot 2 a perched water table would be expected to form above the seal layer. The soil moisture profiles do not show that a perched water table is present. Thus the soil moisture profiles support the hypothesis that vegetation is a significant factor in reducing the occurrence of drainage. This matter was not pursued further in this project, as field observations over longer periods together with a significantly more complicated model would be required to explain the effect of the claystone seal layer.

The model was verified for plot 3 in a similar manner to that described above for plot 2. A different batch of spent shale with a smaller particle size was used to fill this vegetated plot so a soil index of 6.0 was selected account for this. Potential evapotranspiration coefficients were determined from the plot 1 and 2 modelling and the 1986 and 1987 vegetation survey. The bare soil potential evapotranspiration coefficient of 0.34 was used for 1986 because of the slow rate of plant growth. Potential evapotranspiration coefficients of 0.36 and 0.38 were used for the first and second half of 1987 respectively. A potential evapotranspiration coefficient of 0.4 was used for 1988. Figure 5.3 shows the predicted soil moisture contents from the modelling and the corresponding measured data. Both the model predictions and the measured data were more variable than was observed for the other vegetated plots. The characteristic discrepancy observed for the other plots during the first half of 1987 was not present for plot 3.

An explanation for the variability in measured soil moisture contents lay in the calibration of the neutron probe. The calibration was assumed to be the same as for plots 1 and 2. This was an approximation as the spent shale was of a different particle size, the material was slightly dryer when the plot was constructed, the material was less well mixed (it was mixed in a heap on the ground by a backhoe, not in a concrete truck like the material in the lysimeters) and was packed at a lower density. A series of adjustments was made to the calibration curve using the findings of Lal (1974) as a guide. The intercept on the calibration curve was reduced to account for the reduced density, and the gradient was reduced to account for the different soil texture. The value of the soil moisture contents changed with the changing calibration, but their

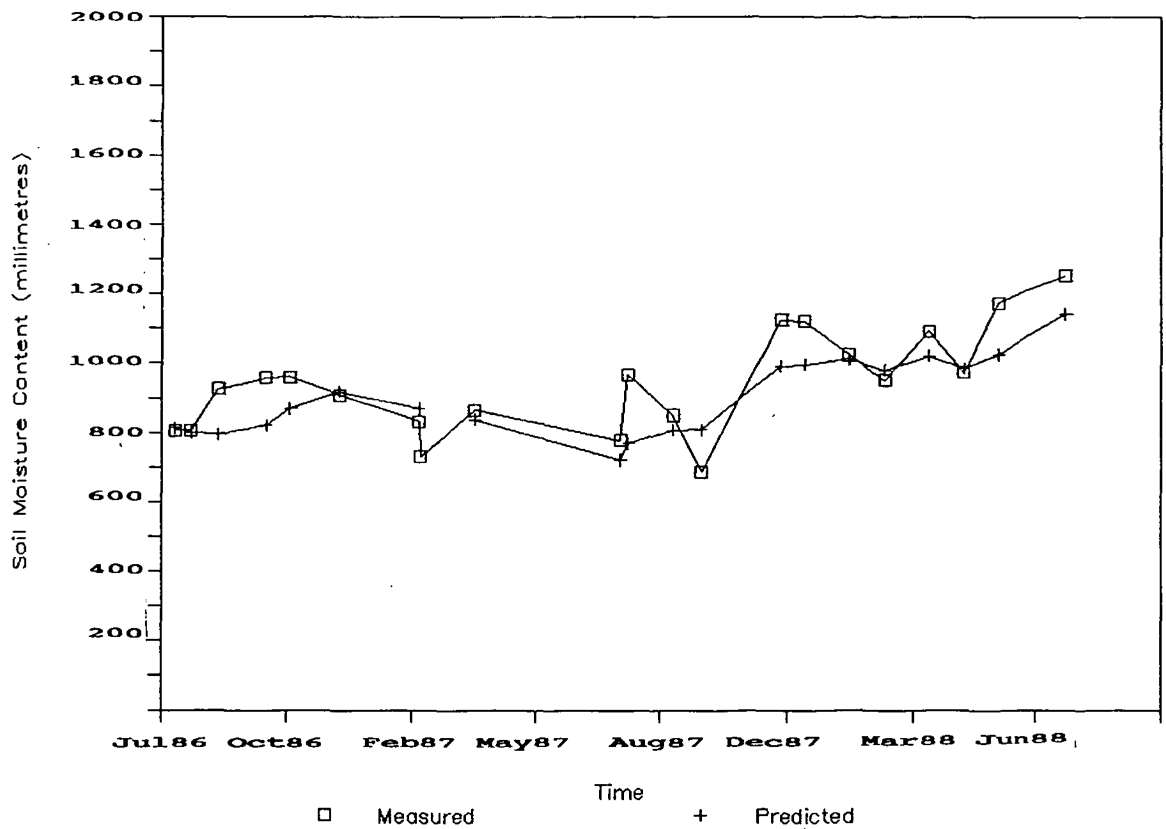


FIGURE 5.3 Measured and Predicted Soil Moisture Content, Plot 3

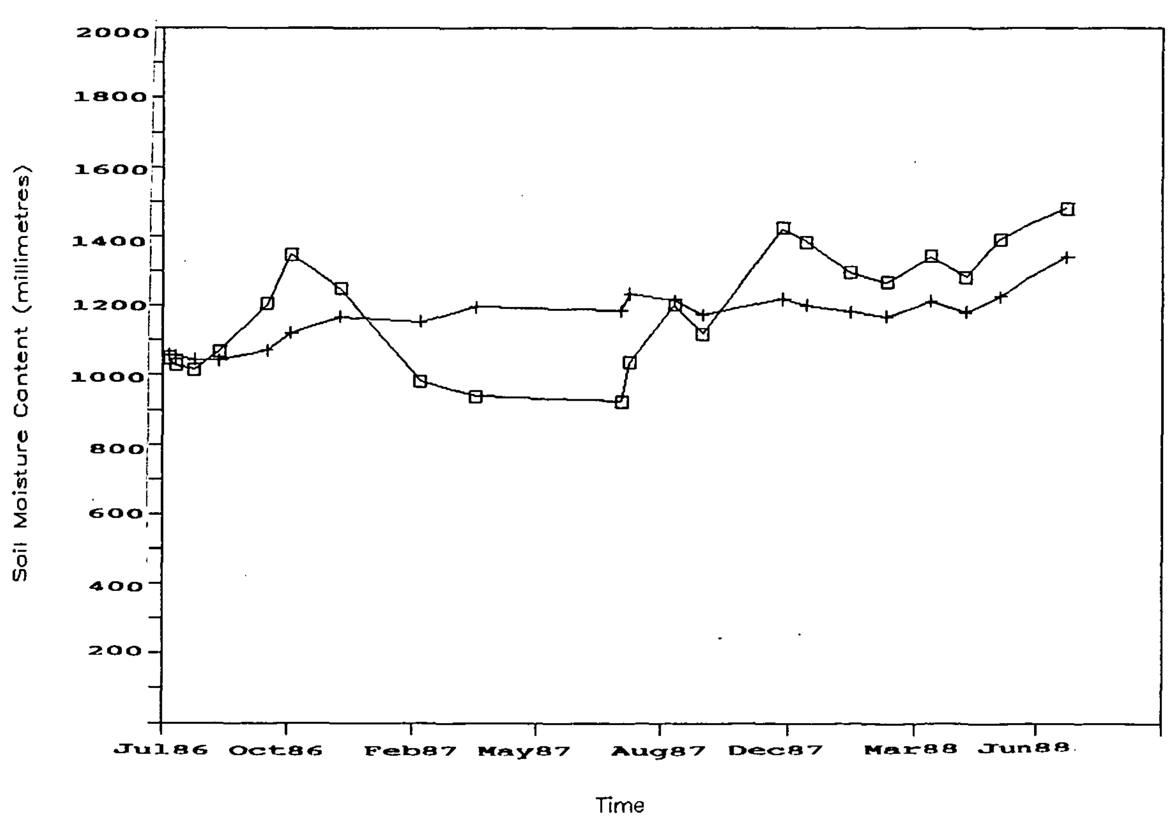


FIGURE 5.4 Measured and Predicted Soil Moisture Content, Plot 4

variability did not. Similarly, the correspondence with the model predictions was not improved. Thus the attempt to adjust the calibration curve to account for the known changes was unsuccessful and the original calibration from plots 1 and 2 was retained for the model verification.

The model predicted the absence of infiltrate. This was consistent with the soil moisture profiles obtained from the neutron probe which showed the lowest 0.5 metres to be dryer than the upper layers of material.

The data verified the model predictions for plot 3.

Plots 4, 5, 6, and 7 were all in undisturbed soil. Examination of the cores extracted by the neutron probe auger showed that the soil material could be classified as clay. Therefore a soil index of 1.5 was used in the model runs for these plots.

The vegetation growth patterns in plot 4, the vegetated area around the lysimeters, were very similar to those observed in the vegetated lysimeter, plot 2. The same value for the potential evapotranspiration coefficients were therefore used for plot 4 as had been verified for plot 2. The soil moisture contents predicted by the model for plot 4 corresponded closely with the measured values until September 1986 (Figure 5.4). The discrepancy observed during the first half of 1987 for plots 1 and 2 was also seen for plot 4. Model predictions were within 10% of the measured values for the latter part of 1987 and for 1988.

Some of the observed discrepancies between the model and the field results could be attributed to the calibration of the neutron probe. The field calibration for the access tubes in plot 4 was unsuccessful, so an approximation obtained from a drum calibration of very similar material was used. There may be heterogeneity in the material which would limit the precision of the neutron probe tube, but averaging of the results from the three neutron probe access tubes in this plot would help reduce the effect of heterogeneity on the field results. These factors reduce the likely correspondence between observed and predicted values to less than 10 %. Thus, the model was a reasonable representation of the field data.

The model predicts no occurrence of infiltration, as was expected from inspection of the soil moisture profiles from the neutron probe data.

Modelling of plot 5 required the selection of two parameters, potential evapotranspiration coefficient and the maximum soil moisture store. The neutron probe data showed the maximum soil water content to 3 metres to be approximately 1910 millimetres recorded in May and June 1988. This was selected as the field capacity. This value was higher than that which was expected from the material properties, and was possibly due to the influence of a dam approximately 30 metres away. Investigation of the possible influence of the dam was beyond the scope of this project.

A potential evapotranspiration coefficient of 0.45 was selected. This was the value that was used for the modelling of plots 2 and 4. The leaf area index, presented in Section 4.6, was less for plot 5 than plot 4. This is reflected in the larger proportion of bare soil in plot 5 (Section 4.7). Thus superficially plot 4 might be expected to have a greater potential for evapotranspiration. Consideration of the type and structure of the vegetation was also necessary however, plot 4 was pasture, whereas plot 5 contained a number of trees up to about 5 metres in height. The root system of the larger vegetation would be likely to extract water over a wider area thus balancing the effect of the larger leaf area index of plot 4. In balance a potential evapotranspiration coefficient of 0.45 was selected.

The model was run and the predicted soil moisture contents compared with the measured values (Figure 5.5). From July 1987 to 1988 the correspondence of the model results and the field result was within 5%. The relative values of modelled and measured soil moisture contents for the first half of 1987 that have been noted above were repeated here. A 20% discrepancy from July to October 1986 was observed. An explanation for this, consistent with the good correspondence observed in later periods, has not been developed. No leachate was predicted by the model for plot 5 under these conditions.

The model for plot 5 was successfully verified by the field data.

The vegetation of plot 6 consisted of less grass cover with more and larger tree species, so although the leaf area indicies were similar for plot 5 and plot 6, the latter would be expected to be able to extract more water from the soil. A potential evapotranspiration coefficient of 0.52 was selected. The maximum soil moisture content was estimated to be 1750 millimetres, approximately the maximum observed soil moisture content. This was a conservative assumption, and would result in the production of leachate earlier than if the soil moisture was set at a higher level.

The model was run producing predicted values that were generally within 20% of the measured vales of soil moisture content (Figure 5.6). The observed and predicted values for the first half of 1987 are consistent with the other plots. The relatively variable correspondence was probably due to the calibration of the neutron probe which was performed in the same way as for plot 4 (above) and has the potential to produce similar effects. The soil moisture contents for plot 6 were fairly high, possibly due to an estuary about 75 metres away or to the calibration.

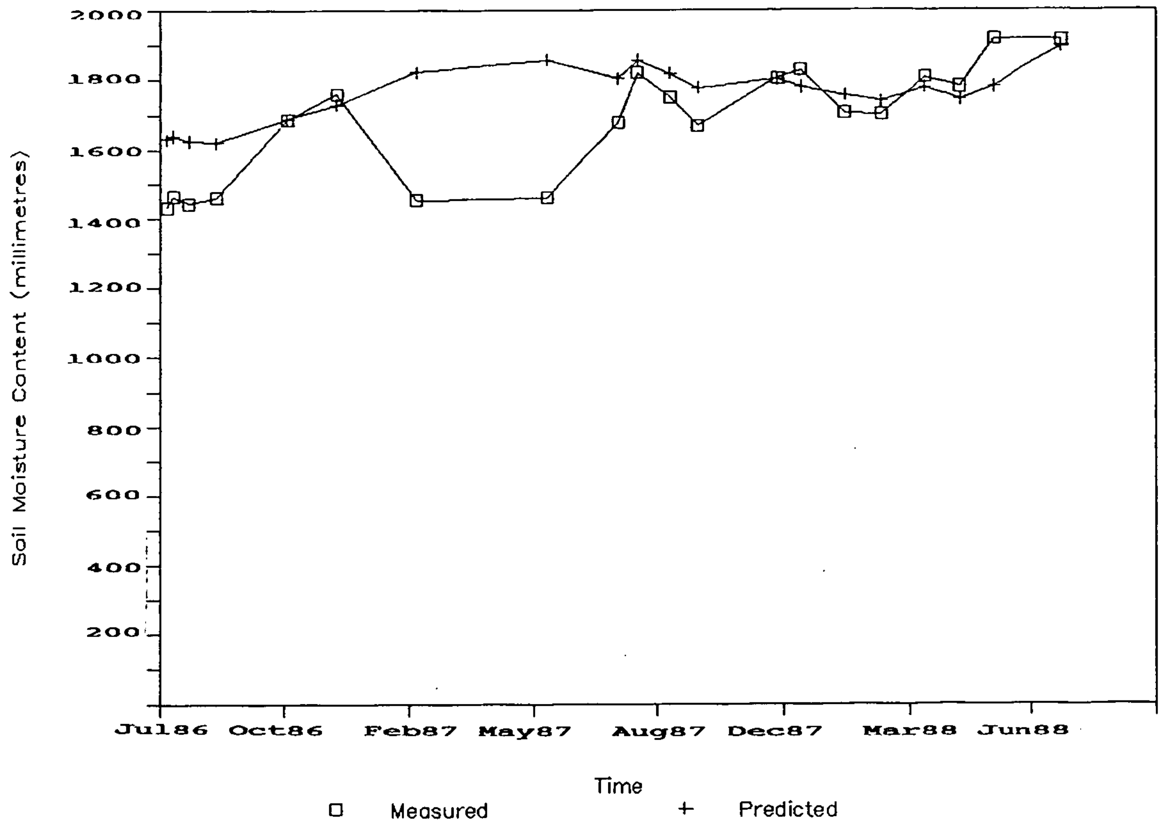


FIGURE 5.5 Measured and Predicted Soil Moisture Content, Plot 5

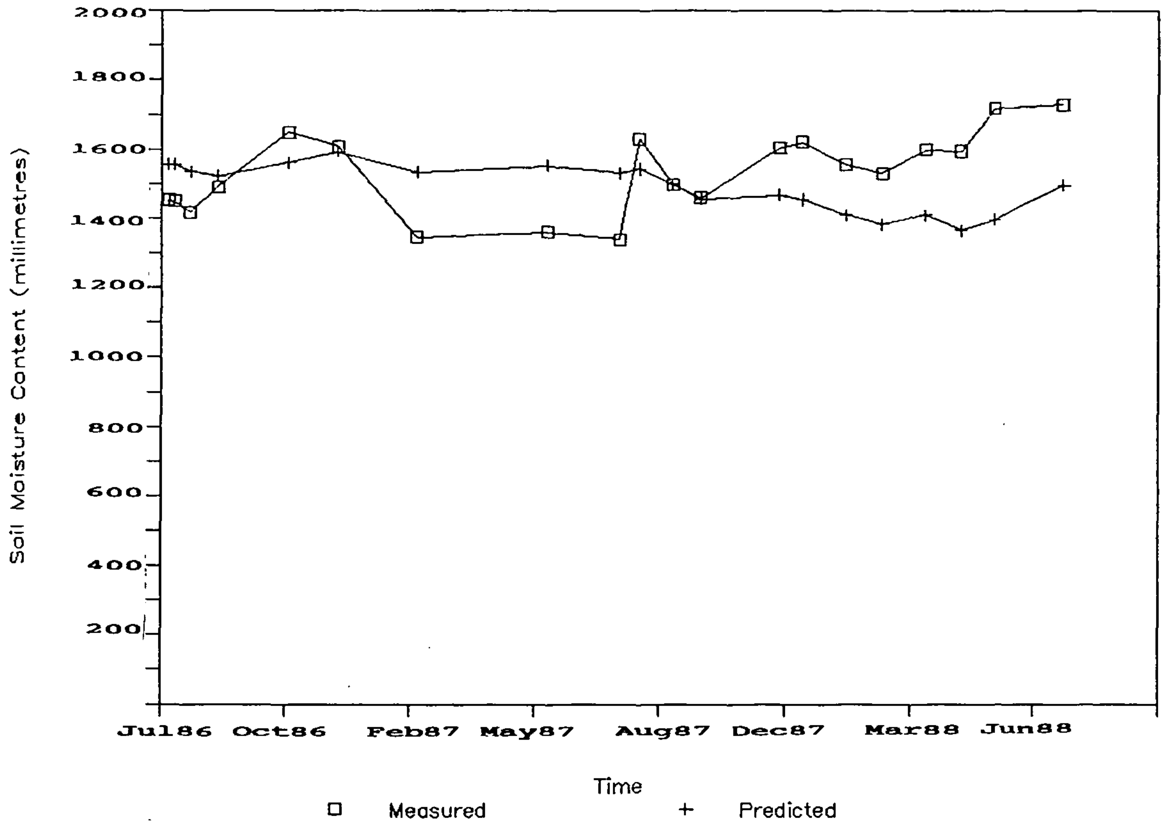


FIGURE 5.6 Measured and Predicted Soil Moisture Content, Plot 6

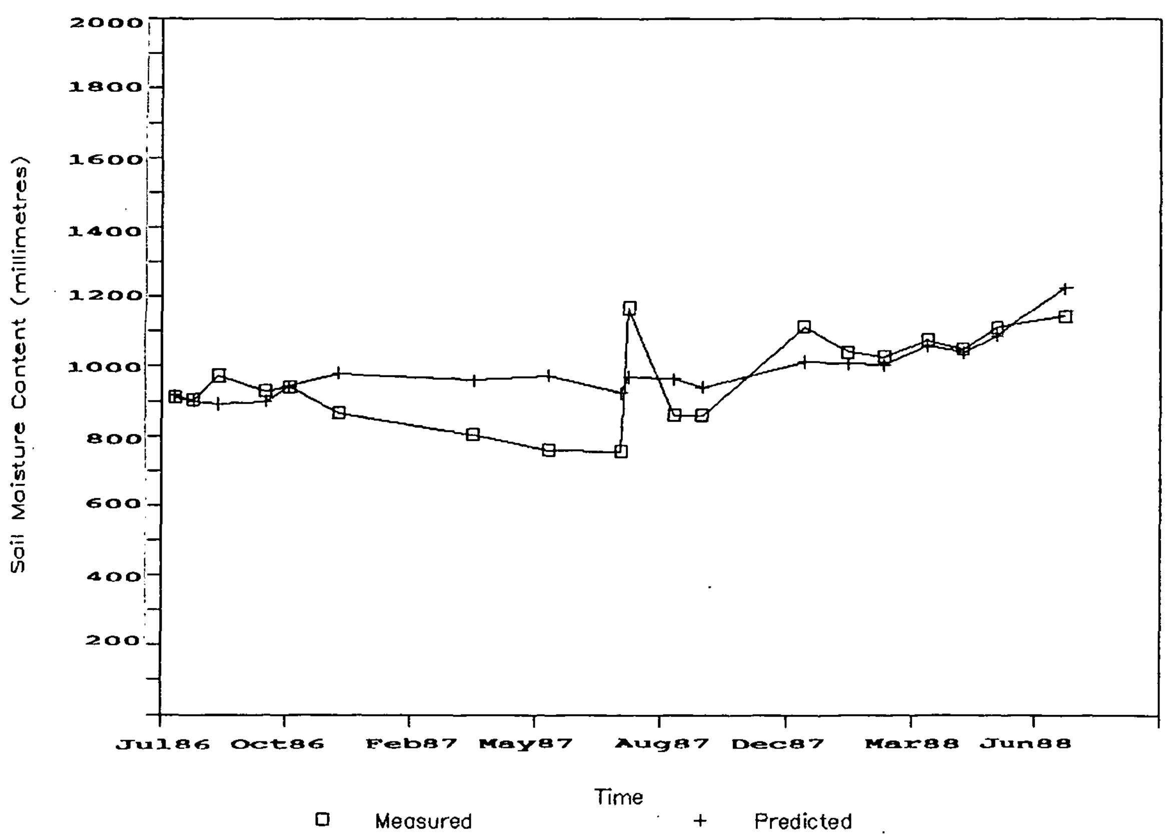


FIGURE 5.7 Measured and Predicted Soil Moisture Content, Plot 7

No infiltration was predicted from plot 6 during this period. Model verification by the field data showed the predictions to be in the same order as the measured values, both higher and lower. The model was verified by the field data.

Three neutron access tubes were originaly installed in plot 7. One was blocked by tree roots in March 1987, and it was not possible to process the data collected from another into a logical format. Operator error was expected to have contributed to this. The vegetation around the remaining tube was logged on July 28, 1987. A potential evapotranspiration coefficient of 0.34 was used for the modelling subsequent to this. Prior to logging a potential evapotranspiration coefficient of 0.55 was used, a value slightly higher than that used in the verified model of plot 6, which was intended to account for the greater spread of the roots of the taller trees at the same time as the lower leaf are index of plot 7.

The value of maximum soil water store of 1500 millimetres that was used for plot 4 was used for plot 7 as it was not adjacent to a dam or estuary. The predicted model values were compared with the measure soil moisture contents (Figure 5.7). These showed good correspondence (generally within 5-10%) except during the first half of 1987, which has been discussed earlier. No leachate was predicted by the model during this period. The model of plot 7 was verified by the field data.

Comparison of the observed and predicted soil moisture contents for the plots with undisturbed soil profiles (plots 4, 5, 6 and 7) indicated that plots 5 and 6 were significantly wetter than plots 4 and 7. The effect of the nearby dam and estuary was considered to be the cause of this. Plot 6 containing older vegetation and allocated a higher potential evapotranspiration coefficient by the model was between 100 and 200 millimetres dryer than plot

5. This was consistent with the expected effect of increasing vegetation on soil moisture. The soil moisture content of plots 4 and 7, neither effected by nearby water, show a similar pattern. Plot 7 containing mature vegetation was consistently between 200 and 300 millimetres dryer than plot 4, containing pasture, for the period of field observations and modelling.

5.1.1 Prediction Accuracy

The accuracy of the predicted soil moisture content compared with the measured soil moisture content is shown in Figure 5.8. All values from all study plots have been included on this graph. The line of best fit (least squares) of the data (excluding February 1987 to July 1987) lies close to the line of measured equals predicted soil moisture content indicating a high level of prediction accuracy. The scatter is generally within 150 millimetres, again indicating good prediction accuracy.

The anomalies in the soil moisture contents measured between February 1987 and July 1987 are emphasised in Figure 5.8. The measured soil moisture content is clearly much lower than predictions. The line of best fit of this data shows a low level of prediction accuracy.

5.2 Long Term Model Predictions

Predictive long term modelling was undertaken in two sections. The first part examined the relationship between drainage beyond the root zone and vegetation age. The second component investigated the effect of changing climate, such as long term increases or decreases in rainfall or evaporation, on drainage beyond the root zone for mature vegetation.

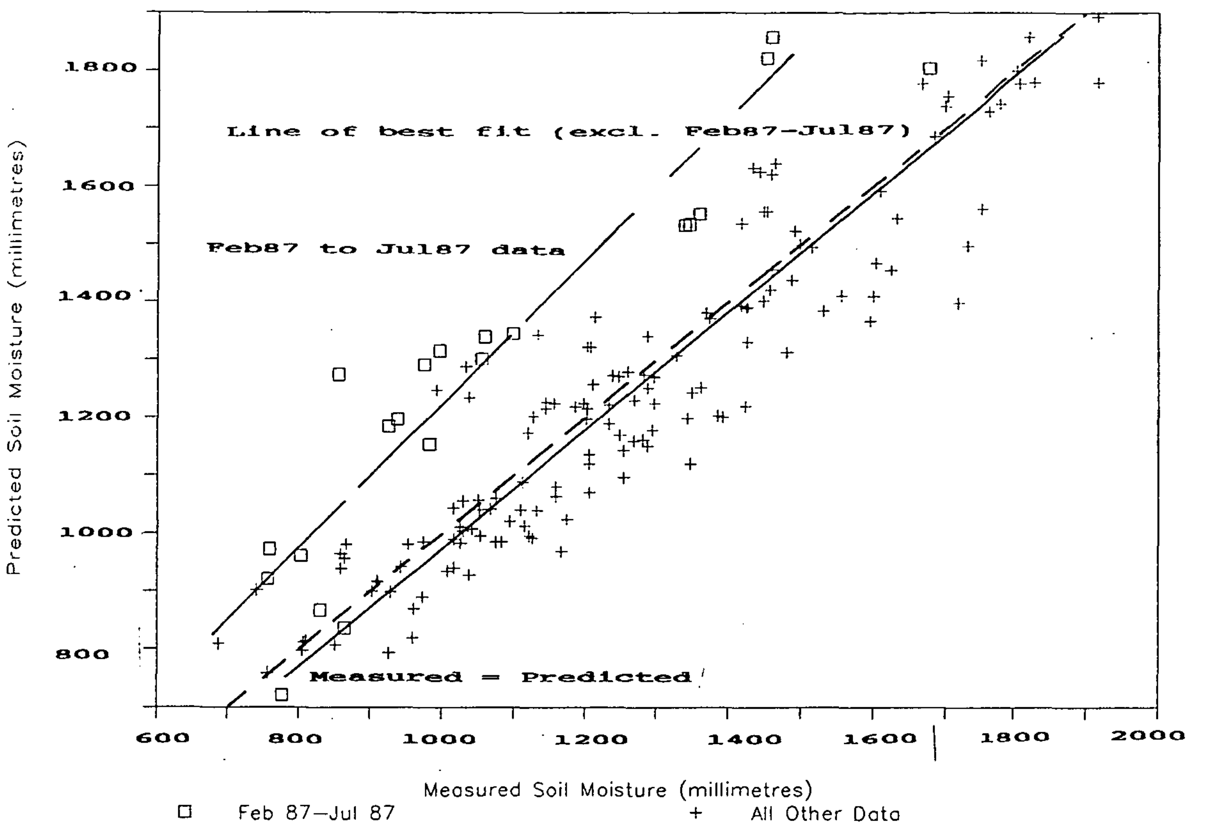


FIGURE 5.8 Relationship Between Measured and Predicted Soil Moisture Content Using Data From All Study Plots

Two assumptions were required to facilitate the long term predictive modelling. The soil index of 3.5 verified (Section 5.1) for plots 1 and 2, the lysimeters containing waste material and set up to represent the surface layers of the planned waste piles, was used for all the long term predictions. The predictions were based on a overburden and combusted shale mixture with no underlying claystone seal layer. The potential evapotranspiration coefficients determined for plots 4, 5, 6 and 7 were assumed to remain the same with the changed soil factor. This assumption was based on the potential evapotranspiration coefficients determined for plots 2 and 4. The potential evapotranspiration coefficients were the same although the soil factors were different.

Rainfall and evaporation data was entered repetitively for a number of years so that all the long term predictive models could be run for a number of years (generally one or two years) to obtain the equilibrium soil moisture content defined in Section 3.5. The models were run for one further year to obtain the predictions for the volume of drainage beyond the root zone and the number of weeks in which drainage occurred.

The volume of drainage was obtained in millimetres, effectively cubic millimetres per square millimetre. To put this in perspective; one millimetre over the surface of a lysimeter is three litres, in comparison one millimetre over the surface of a waste pile 1 kilometre by 1 kilometre is 1000 cubic metres, or one million litres.

The average rainfall (over 108 years) and average evaporation (16 years) given in Section 4.4.2 were used as the rainfall and evaporation inputs to the long term modelling. Rainfall and evaporation were both given as monthly averages and converted to weekly averages using the assumption of uniform daily rainfall and evaporation on each day of the month. The average annual rainfall was 1015 millimetres. The average annual evaporation was 1765 millimetres.

The relationship between drainage and age of vegetation was examined. The frequency of drainage beyond the root zone decreased from a frequency of 34 weeks per year to 6 weeks per year as the age of the vegetation increased from 0 (bare soil) to 15 years (the assumed minimum age of the mature vegetation). The drainage volume decreased correspondingly from 412 to 49 millimetres. Figure 5.9 illustrates both the relationship between age and frequency of drainage beyond the root zone and the relationship between age and quantity of drainage. Thus, the volume of water moving beyond the root zone was predicted as a function of age given particular rainfall and evaporation patterns.These data supported hypothesis 2 given in Section 1.3.

The average rainfall and evaporation given above were used as a baseline to test the effect of changing climate patterns, namely rainfall and evaporation, on model predictions. Variations in rainfall and evaporation were tested separately. Six variations, ±10%, ±25% and ±50%, of the average rainfall and evaporation were tested.

Increasing rainfall increased both the frequency and volume of drainage beyond the root zone. For example, increasing rainfall to 50% above the average increased the frequency of drainage from 6 to 32 weeks per year and volume from 49 to 544 millimetres per year. Reduction in rainfall by 10% resulted in model predictions of no leachate. Extrapolation from Figure 5.10 would indicate that a reduction in average rainfall by 5% would result in a prediction of zero drainage.

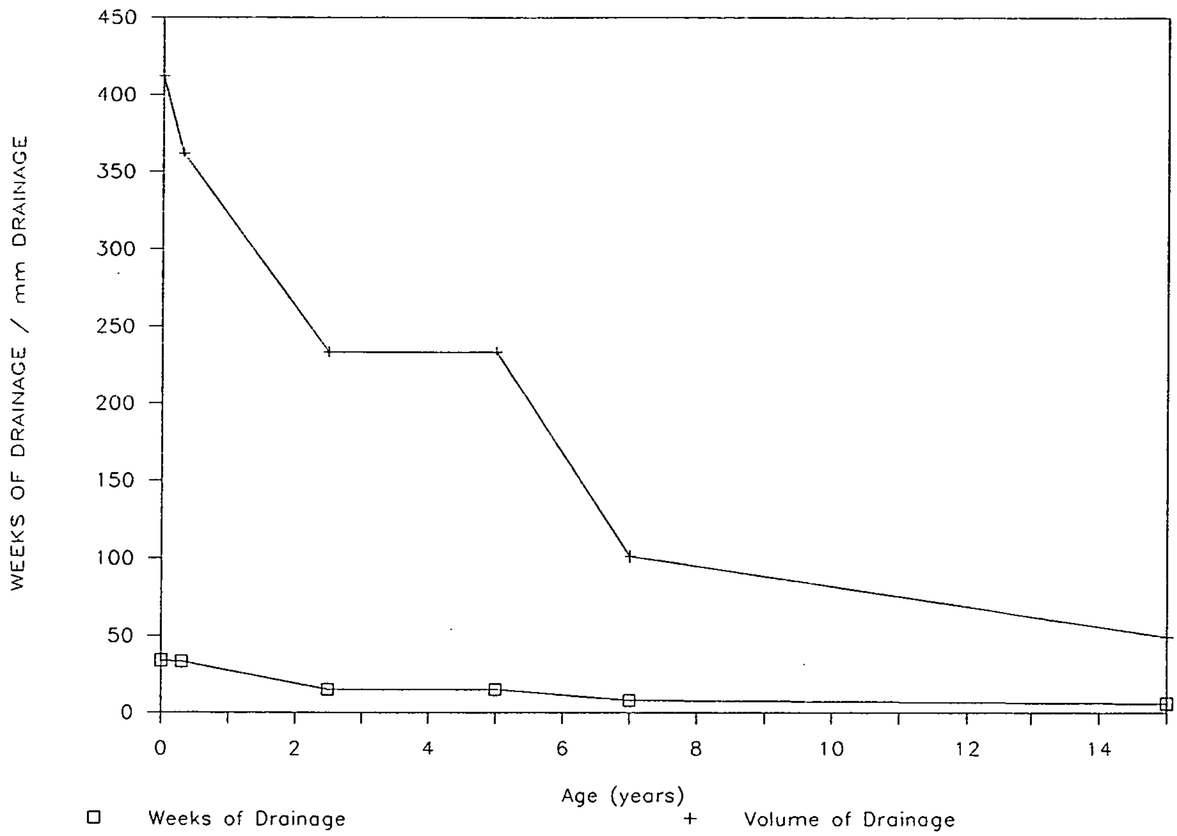


FIGURE 5.9 Relationship Between Drainage Beyond the Root Zone and Vegetation Age

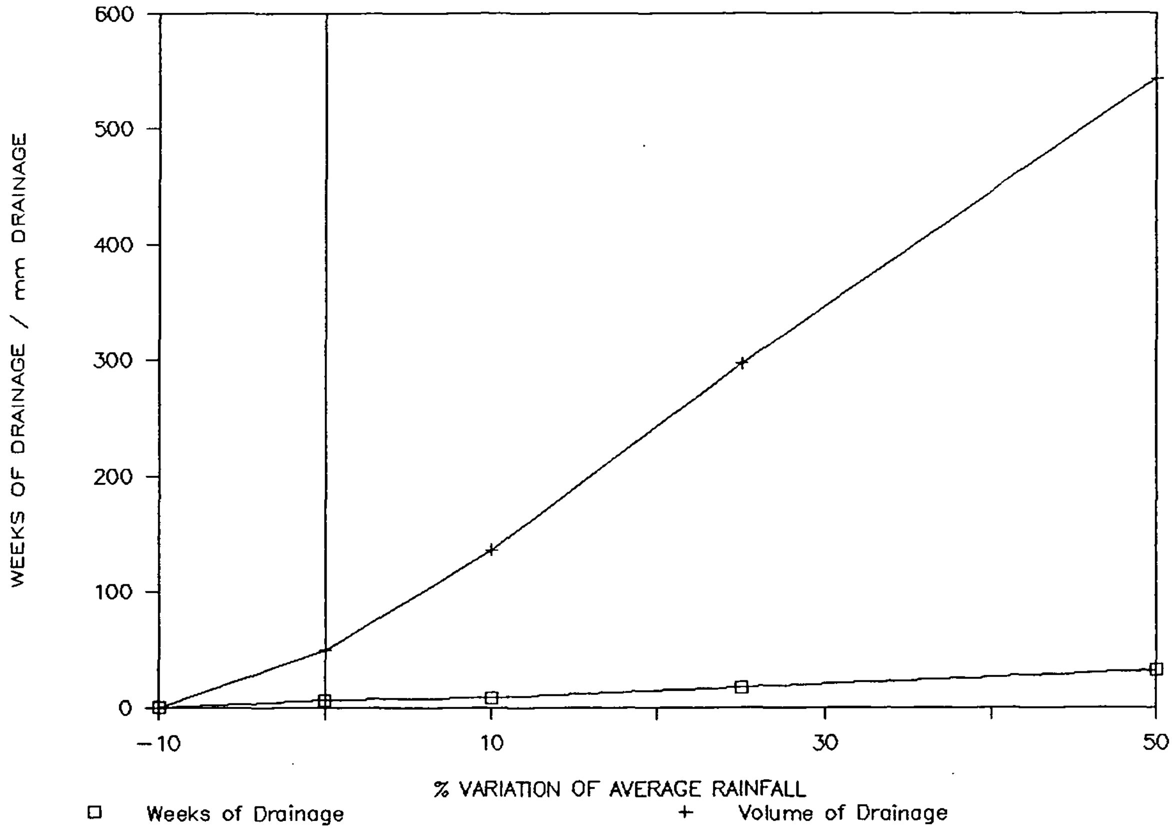


FIGURE 5.10 Relationship Between Drainage Beyond the Root Zone and Variations of the Long Term Average Rainfall

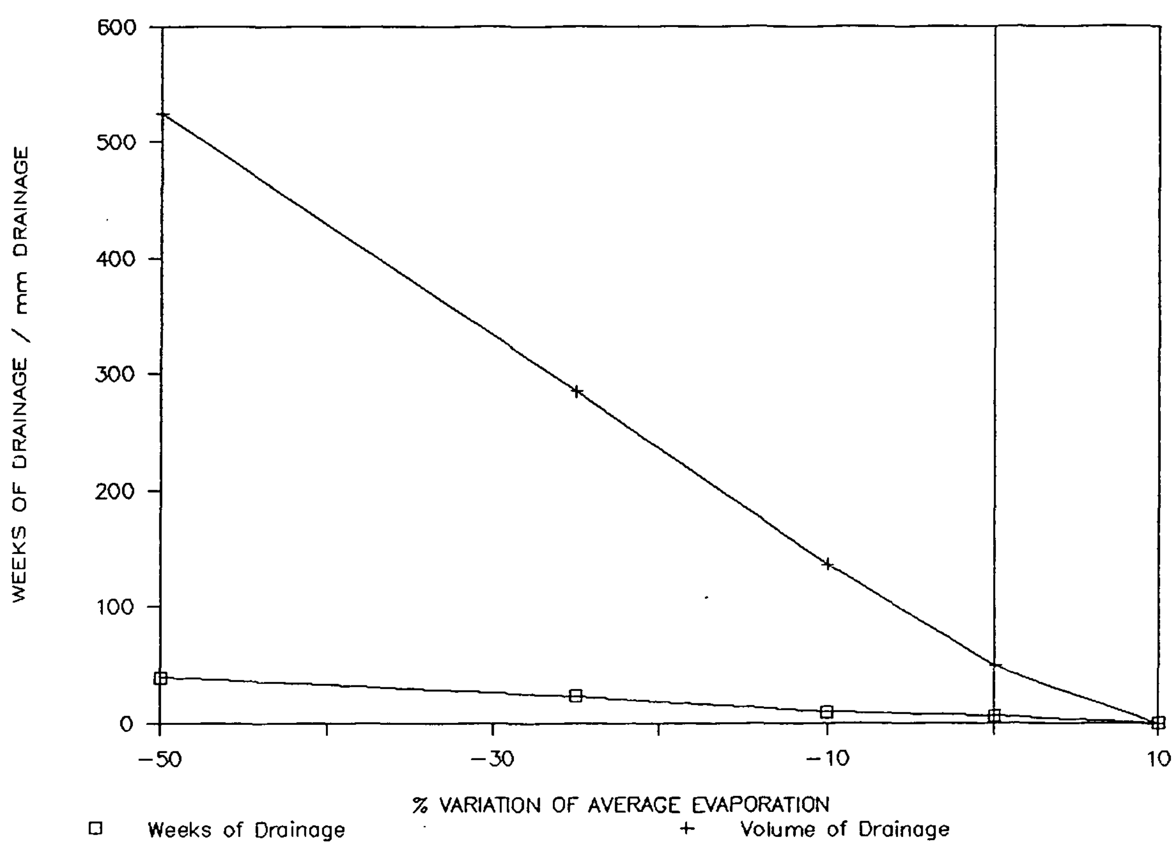


FIGURE 5.11 Relationship Between Drainage Beyond the Root Zone and Variations of the Long Term Average Evaporation

Decreasing evaporation whilst maintaining average rainfall resulted in predictions of increasing drainage beyond the root zone. Halving evaporation increased the frequency of drainage from 6 to 39 weeks per year and increased the volume of drainage from 49 to 525 millimetres. Increasing evaporation by 10% resulted in the prediction of no drainage beyond the root zone. From Figure 5.11 it was determined that a 10% increase in evaporation would result in no drainage

Figures 5.10 and 5.11 show that predictions of the movement of water beyond the root zone as a function of varying rainfall and evaporation patterns are possible for vegetation of a particular age, in this case mature vegetation.

All the model predictions undertaken were based on the occurrence for several years of a particular rainfall and evaporation. The annual rainfall and evaporation occurring prior to the establishment of the equilibrium soil moisture content would not yield predictions of the same quantities and frequencies of drainage as those described here which occurred after equilibrium soil moisture content had been established.

An alternative technique of predicting drainage over long periods that was considered, but not adopted due to time constraints, was to use the actual weekly rainfall and evaporation data collected over these periods and base model predictions on the historical weekly rainfall and evaporation data. Neither method would allow testing of the predictions so the simpler method was used.

5.3 Interface With Other Rundle Waste Dump Models

This research was one element of an extensive program which was designed to model the quality and quantity of leachate from the proposed Rundle waste piles. The results from this work are input data for the the hydraulic and chemical models of the entire waste piles being developed by the University of Queensland. There are several alternatives for interfacing this work with the University of Queensland models:

(a) Manually transferring the output data (soil moisture content and infiltration) into the model of the entire waste piles.

(b) Adapting the coding of WATBAL so that the equations can be directly incorporated into the first part of the model of the entire waste pile.

(c) Developing a simple correlation between rainfall, evaporation and infiltration, verifying the correlation using WATBAL, and incorporating it into the model of the entire waste piles.

The first option does not require additional computer code as it uses WATBAL results directly. It does require time to re-run WATBAL and transfer the results between the two programs each time a sensitivity involving rainfall and evaporation is required. The second option requires extensive programming to effectively incorporate WATBAL into the model of the entire waste piles. The third alternative requires less programming, but would involve developing a correlation that could be verified by WATBAL and would be straight forward.

The University of Queensland will select the most appropriate of these methods based on the requirements of their models and on programming and time constraints.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The Rundle Oil Shale project operated by Esso Australia Ltd. is an example of a project where a comprehensive system of pre-mine planning is being carried out in order to anticipate and mitigate potential problems prior to project commencement. Integral to this planning was the waste dump leachate program, of which this study was a part. The objective of this program is to develop and verify predictive computer models for water and chemical movement within the waste piles. This study developed a model of the vegetated surface layers of the waste piles in order to predict the drainage of water beyond the root zone of the vegetation, and hence the potential for leachate.

Plant, water and soil interactions were the basis of this study. The literature on this topic was broadly divided into two areas. A lot of research had been carried out on plant physiology aspects of plant, water and soil interactions, mostly detailed studies focusing on plant behavior when water was limited. A second thrust to the research was found to be attention to the water remaining in the soil after uptake by plants which was therefore a resource for other purposes such as infiltration through the soil. A number of factors were found to influence these interactions, including soil properties, and vegetation properties such as age, leaf area index, plant size and type and root depth.

The most appropriate model for meeting the objectives of the evapotranspiration project, whilst being compatible with the resources and time available for the project, was a water balance type model. WATBAL, developed by CSIRO was selected for this project. The assumptions inherent in the model were readily apparent and are described in Chapter 3. There was no provision for runoff in the model. Runoff, with the exception of plot 3 where it was subtracted from incoming rain, was accounted for in the assessment of evapotranspiration. This assumption is such that actual field drainage will probably be less than that predicted by the model.

Two hypotheses were put forward in this study. These are stated in full in Section 1.3. The data from the Rundle Oil Shale project supports the first hypothesis: that revegetation of a mining waste dump reduces the water available for leachate generation within the dump. Comparison of the soil moisture profiles obtained from plots 1 and 2 the two lysimeters supports this. The models described in Chapter 5 provided further data to support this hypothesis. Increasing age and size of vegetation decreased the water moving beyond the root zone with the potential for forming leachate.

The modelling described in Section 5.1 provided evidence to support the second hypothesis: that for a given example drainage beyond the root zone can be predicted as a function of season, rainfall event, and age of vegetation. The information gained from the short term model predictions was used as the basis for the long term predictions described in Section 5.2. These long term predictions, although they cannot be tested without considerable expansion of the scope of the study, will be used as inputs to the major waste dump leachate model.

For any given rainfall and evaporation, mature vegetation is significantly more effective in reducing the potential for leachate than grass. For average rainfall and evaporation the presence of mature vegetation rather than grass reduces the number of weeks in which drainage occurs from 15 to 6 and the quantity of drainage beyond the root zone is reduced from 233 millimetres over an area to 49 millimetres. This compares with bare soil where, under the same conditions, drainage is predicted to occur in 34 weeks each year with 412 millimetres draining beyond the root zone.

Following periods of average rainfall and evaporation, 45 millimetres of rain, or more, occurring weekly for 9 weeks would be expected to yield some drainage beyond the root zone for an area of mature vegetation. This assumes that the soil moisture store was at a minimum, for average conditions, prior to the onset of increased rain. Alternatively, approximately 180 millimetres of rain in one week would yield leachate, assuming minimum soil moisture store for average conditions prior to the commencement of rain.

The techniques used in this study, both the field data collection techniques and the modelling, would be suitable for adaption to other mining projects where leachate control is one of the specific objectives of a rehabilitation program. Using these techniques, supplemented with other monitoring of variables such as runoff, the relative effectiveness of the individual elements of the rehabilitation program can be determined.

6.2 Recommendations for Further Work

These recommendations are aimed at improving the efficiency and veracity of future studies of this type, rather than providing suggestions for specific research programs that could be undertaken by the Rundle Project Group.

The methodology of leachate modelling type of projects would be improved by developing the model at the commencement of data collection and running the model in parallel with the evaporation, rainfall and neutron probe data collection. This would flag problems with instrumentation, calibration of instruments or the model much earlier. Superficial examination of the data as it was collected was inadequate to determine the quality of that data compared with previous measurements and anticipated changes.

In view of the considerable expense involved in running remote long term field experiments and the potential heterogeneity of rainfall, evaporation and of the dump materials themselves, a careful assessment of the advantages of information obtained from a future waste pile site must be weighed against expense and the potential for bias due to heterogeneity. A less remote site has considerable advantages for detailed monitoring and ease of repairs. These considerations are particularly important when the local variations of rainfall, even in the relatively small Gladstone - Rundle area are taken into consideration.

Two additional areas of data collection or verification should be considered. Runoff has the potential to make a significant contribution to the water balance, particularly on steeper slopes. More detailed quantification of the relationship of slope, vegetation cover and runoff would enable more accurate determinations of drainage. The ability to incorporate runoff as a separate item would be a major improvement of WATBAL. In this study runoff was assumed to be accounted for in the assessment of evaporation for all plots except plot 3, the runoff plot where runoff had been measured and so could be subtracted from incoming rain. The treatment of runoff is probably conservative. Therefore, drainage may be less than that predicted by the model. The second series of useful information would be laboratory or field verifications of values selected for field capacity for the various study plots.

A useful expansion of the work would be to establish a direct relationship amongst Leaf Area Index, for a particular vegetation type, potential evapotranspiration coefficient and soil moisture content for various rainfall and evaporation conditions. This would require measurement of soil moisture and Leaf Area Index on a frequent basis (perhaps monthly) as well as rain and evaporation.

The veracity of the neutron probe data is dependent on calibration and periodic checking of the data and operator reliability. Operator reliability was important and was a potential reason for spurious results (readings taken at the wrong depth or not taken at all were typical problems).

Two recommendation are specific to the Rundle studies.

(a) The results from the evapotranspiration modeling should be incorporated into the major hydrological and chemical model.

(b) If the lysimeter program is continued beyond the end of 1988, it would be useful to collect one series of neutron probe reading every six months from the vegetated plots so that if required in the future the model predictions can be further tested. The neutron probe collection for plots 1 and 2 (the two lysimeters) should be continued as usual. For all periodic neutron probe measurements particular care is required to document the depths at which the readings are taken and the number of readings at each depth.

(c) The effectiveness of eucalypts in removing water from soil should be compared with other tree species that could be grown on the waste pile materials in the rainfall, temperature and evaporation conditions of the Rundle area. For example, conifers may give satisfactory rehabilitation results under the Rundle conditions and have a higher rate of evapotranspiration than eucalypts, and thus, from the perspective of the water balance be a preferred rehabilitation alternative to the present planning basis. A short literature review of the relative water requirements and evapotranspiration of various vegetation types would be an appropriate approach.

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APPENDIX 1

List of References of Case Studies of Australian Mining Solid Waste Disposal Piles

Acid Mine Drainage	Bell *et al*. 1982, Harries and Ritchie 1982, Miller *et al*. 1983, Finkelman and Monaghan 1984
Captains Flat	Craze 1979, Craze 1977a, Craze 1977b, Craze 1977c, Craze 1978, Keane and Craze 1978
Collinsvale	Charles 1980
Mount Morgan	Trevis 1980
Mt. Lyell	Lake *et al*. 1977, Roberts and Watson 1980
Rum Jungle	Willis 1984, Lucas 1980, Department of Mines and Energy, Northern Territory undated, Goodman *et al*. 1981, Harries and Ritchie 1982, Harries and Ritchie 1983, Ryan 1986, Harries and Ritchie 1987, Bennet *et al*., 1987
Storys Creek and Aberfoyle	Norris *et al*. 1980, Norris *et al*. 1981, Tyler and Buckley, 1973
Uranium Industry/ Ranger Uranium	Lucas 1980

APPENDIX 2

Table A: Neutron Activation Analysis results, Sulphur content and x-ray diffraction results from representative sample of combusted shale (Refer: CSIRO Preliminary Report, Rundle Oil Shale Lysimeter studies)

a) Neutron Activation Analysis Results

Results expressed as ug/g unless otherwise stated.

Na	0.820	+OR-	0.041	%
Mg	1.54	+OR-	0.44	%
Al	6.50	+OR-	0.32	%
Cl	0.698	+OR-	0.986	mg/g
K	1.40	+OR-	0.09	%
Sc	15.8	+OR-	0.8	
Ti	0.48	+OR-	0.11	%
V	86	+OR-	11	
Cr	61.3	+OR-	5.5	
Mn	6.117	+OR-	0.005	%
Fe	5.65	+OR-	0.28	%
Co	24.7	+OR-	1.2	
Zn	69	+OR-	44	
Ga	14.2	+OR-	6.1	
As	15.5	+OR-	1.1	
Br	3.34	+OR-	0.50	
Rb	57	+OR-	12	
Ag	less than		6.5	
In	less than		1.5	
Sb	0.72	+OR-	0.24	
I	less than		11	
Cs	4.80	+OR-	0.77	
Ba	0.534	+OR-	0.084	mg/g
La	23.3	+OR-	1.2	
Ce	47.4	+OR-	2.4	
Nd	17.0	+OR-	5.4	
Sm	5.14	+OR-	0.26	
Eu	1.12	+OR-	0.12	
Tb	0.61	+OR-	0.19	
Dy	less than		1.3	
Yb	2.34	+OR-	0.53	
Lu	0.41	+OR-	0.055	
Hf	3.86	+OR-	0.21	
Ta	0.66	+OR-	0.20	
W	less than		10	
Ir	less than		8.6	ng/g
Au	6.0	+OR-	3.4	ng/g
Hg	less than		0.73	
Th	6.84	+OR-	0.34	
U	less than		3.2	

b) Sulphur Content

0.032 % pyritic sulphur
1.80 % total sulphur

b) X-Ray Diffraction

Mineral composition : quartz

Table B: Neutron Activation Analysis results, Sulphur content and x-ray diffraction results from representative sample of overburden (Refer: CSIRO Preliminary Report, Rundle Oil Shale Lysimeter studies)

a) Neutron Activation Analysis Results

Results expressed as ug/g unless otherwise stated.

Na	0.178	+OR-	0.009	%
Mg	0.30	+OR-	0.13	%
Al	9.49	+OR-	0.47	%
Cl	0.763	+OR-	0.065	mg/g
K	0.931	+OR-	0.077	%
Sc	22.8	+OR-	1.1	
Ti	0.504	+OR-	0.053	%
V	0.139	+OR-	0.069	mg/g
Cr	81.4	+OR-	4.1	
Mn	0.115	+OR-	0.006	mg/g
Fe	3.97	+OR-	0.20	%
Co	8.89	+OR-	0.44	
Zn	0.186	+OR-	0.07	mg/g
Ga	22.1	+OR-	3.1	
As	16.3	+OR-	3.1	
Br	18.8	+OR-	1.1	
Rb	58	+OR-	11	
Ag	less than		8.0	
In	less than		0.49	
Sb	1.08	+OR-	0.18	
I	21.3	+OR-	2.6	
Cs	8.74	+OR-	0.36	
Ba	0.433	+OR-	0.080	mg/g
La	25.5	+OR-	1.3	
Ce	60.4	+OR-	3.0	
Nd	27.9	+OR-	6.6	
Sm	9.31	+OR-	0.47	
Eu	1.91	+OR-	0.12	
Tb	1.11	+OR-	0.19	
Dy	4.69	+OR-	0.30	
Yb	4.69	+OR-	0.41	
Lu	0.74	+OR-	0.18	
Hf	5.97	+OR-	0.50	
Ta	0.81	+OR-	0.22	
W	2.05	+OR-	0.92	
Ir	less than		11	ng/g
Hg	less than		0.96	
Th	10.8	+OR-	0.5	
U	2.5	+OR-n	1.3	

b) Sulphur Content

0.011 % pyritic sulphur
0.30 % total sulphur

b) X-Ray Diffraction

Mineral composition : quartz, clay

APPENDIX 3: EXAMPLE WATBAL MODEL OUTPUT

RUNDLE WATBAL WATMODL INPUT VALUES 1987 - 1987

MAXST	1500	MAXIMUM AVAILABLE SOIL MOISTURE STORAGE.
PTMM	0	IF PTMM IS GREATER THAN ZERO THE RAINFALL DATA IS CONVERTED FROM POINTS TO MILLIMETRES.
UNITS	MM	UNITS IN WHICH THE DATA ARE TO BE PROCESSED.
NCATCH	0	IF NCATCH IS NOT ZERO THE RAINFALL DATA IS MULTIPLIED BY NCATCH TO ALLOW CALCULATION OF THE WATER BALANCE OVER A LARGER CATCHMENT.
NWFIRST	1350	SOIL MOISTURE STORAGE LEVEL BEFORE PROCESSING THE FIRST WEEK OF DATA.
NOPRINT	0	IF GREATER THAN ZERO THE LINE PRINTER LISTING FOR WATMODL IS SUPPRESSED.
ISW2	1	IF ISW2 IS ZERO 100 STEPPED VALUES FOR AETCF MUST BE PRESENT. SEE AETCF BELOW.
SOIL	3.50	IF BLANK A VALUE OF 3.5 IS USED AS A SOIL INDEX VALUE AND IS ONLY INPUT WHEN ISW2 IS GREATER THAN ZERO FOR THE CONTINUOUS FUNCTION USED SEE BELOW.
IRR	0	IRR IS SET TO THE PERCENTAGE OF THE SOIL MOISTURE STORAGE (MAXST) THAT IS REQUIRED TO BE MAINTAINED UNDER IRRIGATION.
IRRGAP	1	IRRGAP IS THE NUMBER OF WEEKS BETWEEN IRRIGATION WHEN IRR IS GREATER THAN ZERO.

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PETCF 52 WEEKLY POTENTIAL EVAPOTRANSPIRATION COEFFICIENTS.

.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
.52	.52								

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AETCF 100 ACTUAL EVAPOTRANSPIRATION COEFFICIENTS. NOT REQUIRED.

CONTINUOUS FUNCTION IS USED TO CALCULATE ACTUAL WATER DEMAND USING THE FORMULAE

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ADJ = 1.0 / ( 1.0 - EXP( -3.50 ))
REL = ( CURRENT RAIN + STORAGE ) / MAXIMUM WATER STORAGE
AET = ADJ * ( 1.0 - EXP( -3.50 * REL ))
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EVP 52 ESTIMATED MEAN WEEKLY EVAPORATION VALUES.

29.	29.	29.	29.	29.	23.	23.	23.	24.	25.
25.	25.	25.	28.	28.	28.	28.	23.	19.	19.
19.	18.	17.	17.	17.	18.	20.	20.	20.	20.
31.	33.	33.	33.	32.	32.	32.	32.	31.	27.
27.	27.	27.	40.	45.	45.	45.	38.	29.	29.
29.	29.								

1WATER BALANCE OUTPUT IN MM RUNDLE 1987

WK	EVAP	CF	ET	P	+	-	C-	ST	++	C++	RST
1	29.	.99	15	2		13	13	1337			89
2	29.	.99	15	3		12	25	1325			88
3	29.	.98	15			15	40	1310			87
4	29.	.99	15	38	23			1333			89
5	29.	.99	15	13		2	2	1331			89
6	23.	.99	12	8		4	6	1327			88
7	23.	.99	12	20	8			1335			89
8	23.	.99	12	4		8	8	1327			88
9	24.	.99	12	46	34			1361			91
10	25.	.99	13	9		4	4	1357			90
11	25.	.99	13	1		12	16	1345			90
12	25.	.99	13	15	2			1347			90
13	25.	.99	13	4		9	9	1338			89
14	28.	.99	14	19	5			1343			90
15	28.	.99	14	5		9	9	1334			89
16	28.	.99	14	9		5	14	1329			89
17	28.	.99	14	46	32			1361			91
18	23.	.99	12	4		8	8	1353			90
19	19.	.99	10	1		9	17	1344			90
20	19.	.99	10	10	0			1344			90
21	19.	.99	10	1		9	9	1335			89
22	18.	.99	9	3		6	15	1329			89
23	17.	.99	9	5		4	19	1325			88
24	17.	.98	9	2		7	26	1318			88
25	17.	.98	9	3		6	32	1312			87
26	18.	.98	9			9	41	1303			87
27	20.	.98	10			10	51	1293			86
28	20.	.98	10			10	61	1283			86
29	20.	.98	10			10	71	1273			85
30	20.	.98	10	56	46			1319			88
31	31.	.98	16	4		12	12	1307			87
32	33.	.99	17	32	15			1322			88
33	33.	.98	17	2		15	15	1307			87
34	33.	.98	17	1		16	31	1291			86
35	32.	.98	16			16	47	1275			85
36	32.	.98	16	1		15	62	1260			84
37	32.	.98	16	1		15	77	1245			83
38	32.	.97	16			16	93	1229			82
39	31.	.97	16			16	109	1213			81
40	27.	.97	14	3		11	120	1202			80
41	27.	.97	14	20	6			1208			81
42	27.	.98	14	41	27			1235			82
43	27.	.97	14			14	14	1221			81
44	40.	.98	20	43	23			1244			83
45	45.	.98	23	51	28			1272			85
46	45.	.98	23	5		18	18	1254			84
47	45.	.98	23			23	41	1231			82
48	38.	.98	19	20	1			1232			82
49	29.	.97	15			15	15	1217			81
50	29.	.97	15	3		12	27	1205			80
51	29.	.97	15	1		14	41	1191			79
52	29.	.97	15	35	20			1211			81