THE INFLUENCE OF LANDFILL COVERS ON THE GENERATION OF LEACHATE

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

J Blight 15/1/92

ABSTRACT

World trends in the landfilling of municipal solid waste, and the design of landfill covers are reviewed. Current approaches to solving leachate problems associated with landfills emphasise the use of landfill liners and leachate collection systems.

The installation of liner and leachate treatment systems is expensive. Furthermore, the lives of such systems are likely to be shorter than the time over which the landfill will continue to emit pollutants. The use of landfill covers (which are relatively cheap) to eliminate or minimise leachate production is therefore an attractive proposition. The principle behind using covers to solve leachate problems is their ablity to alter the water balance of the landfill.

The principle of the water balance is reviewed. Existing methods of computing each component of the water balance, as well as methods of calculating the movement of moisture in porous media, are discussed.

A field study of the water balance for a particular landfill is described. In the study, geotechnical and geohydrological properties of the landfill were measured. Moisture and contaminant migration within the landfill were studied by sampling the landfill profile directly, and by monitoring suction in situ. Infiltration into, and runoff from the surface of the landfill have also been measured.

The results of the field study indicate that the landfill is not producing leachate, and that the use of a simple soil cover of appropriate material is adequate to eliminate leachate production, under suitable climatic conditions.

Predictions of leachate generation for the site have been made using current methods of computing the water balance. These predictions are compared to the results of the field tests.

The major short-comings of current methods of computing moisture movement in landfills and landfill water balances are discussed. Recommendations for improving the evaluation of landfill cover performance are made.

CONTRIBUTIONS AND PERSONAL ACHIEVEMENT

I have, during the course of this project gained a very good insight into the processes of moisture movement in unsaturated soils, and the processes governing water balance. I have also learnt much about municipal solid waste landfilling. The project has provided me with experience in laboratory and field experimentation. It has also given me experience in the scientific and technical writing, and provided an opportunity to present research findings to the public. Co-operating with academics of disciplines other than engineering had been a useful and illuminating experience.

I feel that I have contributed a better understanding of the processes of moisture movement and water balance in landfills to the discipline of solid waste management. It is hoped that the findings of this research will lead to more cost-effective design of landfill covers for South Africa, and other countries with similar climates.

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Lastly, I need to thank my brother, Geoff, for assissting me with the diagrammes.

SUMMARY OF CONTENTS

This dissertation is divided into four parts as follows:

Part one consists of two chapters and deals with a literature review on current landfilling practice. Part two comprises five chapters, dealing with a literature review of methods of computing water balances, and moisture movement in porous media. Part three describes field tests undertaken at Linbro Park landfill site, to assess the water balance. Computations of the water balance are compared to the field data. Part three comprises five chapters. Part four comprises one chapter only. In this chapter, moisture and contaminant migration in Coastal Park landfill are discussed

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INTRODUCTION

The world's population has been increasing rapidly for centuries, and has become more and more consumer orientated. This has led to a continual increase in the production of goods. Changes in technology and society have led to an increase in demand for disposable, and packaged goods. These goods and the packaging ultimately become waste. The increased production of goods has therefore lead to increased waste generation.

A large proportion of society's waste is produced in our households. Things such as food waste, garden waste, paper, cans, bottles, plastic bags, form part of our refuse. If not collected, and disposed of in a sanitary manner, vermin and disease are likely to abound.

Man's solution has always been to dump his refuse somewhere, anywhere, out of the way. Seas, rivers, and tracts of unused land, (often otherwise unusable land such as marshland or old quarries) have been favourite dumping places.

Household refuse has, until recently been thought of as 'harmless', if dumped out of the way. It is now known that these 'harmless' wastes are capable of polluting the environment.

Apart from those types of 'harmless' waste mentioned above, our household waste contains some toxic materials. Paints, solvents, batteries, printing inks, pesticides, refrigerants, polishes, disinfectants, adhesives, pool chemicals, are some of these, which make household waste anything but harmless.

The realisation that our wastes are threatening our groundwater, surface waters, and atmosphere has caused society to seek safer ways of managing its waste.

Those waste technologies which are in common use at present are: incineration; recycling; and landfilling. Each of these, however, has its own drawbacks.

Incineration reduces the volume of waste substantially, but noxious gases can be given off into the atmosphere. The residues from the process have to be disposed of by landfilling, and can then produce noxious leachate. Incineration also involves the expense of building and running an incinerator.

Recycling presents the difficulty of separating out different types of waste. Also, the quality of recycled products is not always as high as those made from virgin materials, and it may be more expensive to recycle goods, than it is to produce them from new materials. In any event there will always be some proportion of waste which cannot be recycled.

At present the most popular waste disposal technology in the world, and certainly in South Africa is that of landfilling. Landfilling uses a lot of land, usually within city limits. Unless otherwise useless sites, (e.g. worked out quarries) are used, landfilling must take place on sites which might otherwise be used for housing, or industry. The major problem which accompanies landfill sites is, however, the generation of leachate. Leachate is a polluted liquid which is formed as water percolates through the waste. If it is not intercepted, collected and treated, it may enter groundwater systems and surface waters and pollute them. Flammable and reactive gases which are emitted from landfills can also be problematical.

Landfilling, however, remains the most cost-effective method of waste disposal in most parts of the world. Increased awareness of its attendant problems, and the solution of these problems by scientific developments, as well as more careful site selection, and site management, may lead to safer landfills for the future.

The work described in this dissertation is aimed at minimizing problems caused by leachate, produced by municipal waste landfills.

CHAPTER 1

REVIEW OF LANDFILLING PRACTICE

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1 POLLUTION BY LANDFILLS

The principal concern associated with the practice of landfilling is the question of pollution. In assessing the likely impacts of pollution, the nature of substances emitted (and therefore the nature of the wastes discarded, and the changes they undergo within a landfill), as well as the mechanisms of transport of pollutants, need to be known.

1.1 Quantities and Composition of Refuse

The sheer quantity of waste which is produced in the world is worrying when one considers that it has to be disposed of somehow, and in disposing of it pollution is likely to be generated.

Quantities of municipal waste generated in the world today are of the order of 0.5 kg to 2.5 kg per capita per day. South Africa produces an estimated 1 kg of municipal refuse per person, per day, and a total of 12 to 15 million tons per year.(Carra and Cossu, 1990*; CSIR, 1991)

Paper comprises between 20% and 50% of municipal waste (by mass), worldwide. The figure for glass lies between 5% and 15% . Figures for plastic are similar, while metal forms between 2% and 10% of world municipal waste. Organics make up between 10% and 45% of the world's municipal waste. (Carra and Cossu, 1990; Plastics Federation of South Africa, 1990)

* Survey published 1990, carried out in Austria, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Poland, South Africa, Sweden, Switzerland, UK, USA

The corresponding figures for South Africa are:

paper: 15%-35%
glass: 12%
plastic: 10%
metal: 8%
organics: 30%-45%
(Carra and Cossu, 1990)

In some communities in South Africa ash forms a major portion of household waste - up to 45%. (Hojem, 1988)

The majority of the paper, glass, plastic and metal does not decompose within a landfill. Noxious substances are, however released from these materials.

Small quantities of toxic materials are present in municipal waste. Paints, printing inks, solvents, batteries, pesticides, refrigerants, disinfectants, adhesives, pool chemicals are examples of sources of such substances.

The release of readily bio-degradable organic substances from a landfill constitutes a threat to the environment also. When these substances enter groundwater or surface water they decompose, depleting the oxygen in the water body. The oxygen depletion damages ecosystems dependent on the water body.

1.2 Decomposition Mechanisms

Within the body of a landfill, chemical, physical, and biological processes occur which cause the waste to decompose. The fact that the waste within a landfill is not inert, causes pollutants to be emitted. Water plays a big role in the generation and transport of pollutants. Moisture entering the landfill percolates through the waste, extracting contaminants, to form 'leachate' which may eventually reach and pollute the groundwater in the region.

Gases are also formed by decomposition processes within the landfill. These move out of the tops and the sides of the landfill into the atmosphere and groundwater.

The processes by which substances are extracted, and leachate and gas are generated are described below.

1.2.1 Physical and Chemical Decomposition

Physical decomposition occurs mainly by rinsing of materials from the waste. Chemical decomposition includes chemical reactions such as precipitation, adsorption, desorption, and dissolution. The leachate composition affects the degree to which materials in the landfill dissolve. pH and oxidation-reduction potential are important controlling parameters in this.

1.2.2 Biological Decomposition

Biological decomposition is the major mechanism by which refuse decomposes in a landfill. Biological decomposition also affects chemical and physical decomposition, because it affects variables such as pH and oxidation-reduction potential.

Biological decomposition occurs in three major phases: the aerobic, the facultative anaerobic, and the methanogenic anaerobic phases. These stages are described in many texts (eg Ham and Barlaz, 1987). A brief description is given below.

Aerobic decomposition occurs for a relatively short period after the refuse has been placed on the landfill. It proceeds for only as long as there is oxygen available within the refuse. Most of the oxygen comes from the air incorporated in the refuse during placement. During this phase carbon dioxide and heat are produced. Temperatures may rise to 50^0 - 70^0 C. Partially degraded organics are also produced. This causes leachate produced during this phase to be slightly acidic, and to have a high chemical oxygen demand (COD). The acidic nature of the leachate enables it to leach out more organics and also metals.

Facultative anaerobic decomposition occurs when the availability of oxygen has been reduced to the point where it no longer supports a predominantly aerobic decomposition process. Facultative organisms prefer the presence of oxygen, but can live without it. Carbon dioxide is still produced during this phase, the temperature drops somewhat, and large amounts of partially degraded organics, especially organic acids are produced. This causes the leachate to increase in acidity, pushes its chemical oxygen demand (COD) up, and causes a lot of organics and inorganics to be leached out.

The final stage of decomposition is the methanogenic phase. Methanogenic bacteria cannot tolerate the presence of oxygen. They convert partially degraded organics (arising from facultative anaerobic organisms) to methane and carbon dioxide. This causes the acidity and the COD of the leachate to drop. The pH of the leachate approaches neutrality, and fewer substances are leached from the wastes.

Theoretically, a stage is reached when a landfill will no longer emit pollution in concentrations which are harmful. It is, however, estimated that it takes centuries to reach this stage. (Belvi and Baccini, 1987)

2 LANDFILLING PHILOSOPHIES

The decomposition processes discussed above cause substances which are potentially harmful to the environment to be emitted. In order to try and minimise these emissions, specific approaches to landfilling are adopted.

One scheme is to attempt encapsulation, or total containment of the waste. The 'dilute and attenuate' philosophy, the 'final storage' concept, and the practice of co-disposal of different types of waste are other landfill strategies.

2.1 Containment

The goal of this strategy is to minimize leachate generation, and to remove and treat any leachate which is generated. The former objective is usually achieved by encouraging drainage and limiting infiltration, while the latter is achieved by means of bottom liners, and underdrainage systems. The flaw in this concept lies in the fact that the lifetimes of liners and top caps is limited. Furthermore, it may imply perpetual collection and treatment of leachate.

2.2 'Dilute and Attenuate'

Another approach is the so-called 'dilute and attenuate' strategy. This strategy relies on chemical, physical, and biological processes operating within the wastes, and the underlying soils. The properties of the waste disposal site are of importance to the attenuation process, and sites are chosen for their natural abilities to attenuate pollution.

Also of importance are the biological degradation processes operating within the waste. It is preferable to control these so as to gain maximum benefit from them.

This method cannot be relied upon solely, since the ability of the waste body and the site to attenuate pollutants may not be great enough to protect surrounding areas.

2.3 'Final Storage'

The 'final storage' concept relies on the containment principle, until the biological, physical chemical processes within the wastes have 'cleansed' it, to a degree where emission of pollutants from the landfill are low enough not to harm the environment. Studies show, however, that this could take several centuries to achieve. In pursuing this philosophy it is, therefore of interest to speed up reaction rates and so reduce the time until 'final storage ' quality is reached. (Belvi and Baccini, 1987; Belvi and Baccini, 1989, Cossu et al, 1987)

2.4 Co-disposal

The practice of co-disposing of certain types of toxic or otherwise hazardous waste with municipal waste is a controversial one. Some argue that by practising co-disposal, one causes the entire body of waste to become hazardous, and so increases the risk of pollution. It has, however been shown that co-disposal of certain types of waste, (such as ash, phenolic compounds, and alkaline sludges) has a beneficial effect on the degradation and attenuation of problematical constituents of both the hazardous waste and the municipal waste.(eg Pohland, 1989; Cossu et al, 1989; Boari and Mancini, 1987)

The application of these philosophies is constrained by practical problems, which are discussed in more detail below. A combination of these approaches may be used in an attempt to combine their strengths and eliminate their weaknesses.

3 PRACTICAL PROBLEMS ASSOCIATED WITH LANDFILLING

3.1 Liners and leachate collection systems

Liners are used extensively on waste disposal sites, in an attempt to stop the migration of leachate into areas surrounding landfills. Liners are usually used in combination with drainage systems. Drains serve to reduce the hydraulic pressure gradient across the liner (and so reduce seepage), collect leachate, and sometimes act as leak detection layers, beneath liners.

Materials used for liners and drainage systems may be classified as 'natural', or 'synthetic'. Synthetic liners include rubbers, bitumens, polyethylenes, and polyvinyl chlorides. (Cadwallader and Barker, 1989) A variety of synthetic, woven and non-woven geomembranes are used as drainage layers. Clays and bentonites are commonly used natural liner materials, while sands and gravels are natural materials which are commonly used for drainage layers.

Liners and drains made from both synthetic and natural materials are subject to degradation. Solutions containing acids (organic and inorganic), bases, ionic substances, polar molecules, and such like are known to affect the integrity of synthetic and natural materials.(eg Korfiatis et al, 1986; Daniel and Shackelford, 1987; Cancelli et al, 1987) This may cause the liner or drain to lose effectiveness.

Some synthetics appear to be more resistant to chemical attack than natural materials,(eg Tisinger and Dudzik, 1989) but their long term durability has not yet been proved.

Laboratory tests show that much lower permeabilities may be achieved by using synthetic liners (eg Faure et al, 1989.) Synthetic membranes may be torn, or punched during construction, or during settlement of the body after construction. The seams of such materials are also a weak point. These materials also have the disadvantage of being expensive.

Clay liners are difficult to construct such that they are uniform and contain no clods or cracks which would act as preferential drainage paths (Dunn, 1986). Clays have an advantage over synthetic materials in that they appear to possess self-healing properties.

Problems experienced with drains include clogging. Blockages may be caused by particles washed into the drains, or by the growth of organisms within the drain (eg Tisinger and Dudzik, *1989*; Koerner and Koerner, 1989).

One of the major drawbacks of using liners, and drainage systems, is that leaks and blockages are extremely difficult to repair, since they are buried beneath a considerable depth of refuse. Another disadvantage is the expense of installing such systems.

3.2 Leachate Treatment

Once leachate has been intercepted and collected by means of the drainage and liner systems, it needs to be treated to remove organic and inorganic substances before it can be safely discharged.

Popular methods for leachate treatment involve the use of aerated lagoons, evaporation, reverse osmosis, flocculation, adsorption, and anaerobic digestion. (eg Doedens and

Cord-Landwehr, 1987; Jans and van der Schroeff, 1987; Ehrig, 1987; Blakey and Marais, 1987) Usually one of these processes is not sufficient by itself to reach desirable effluent standards, and a combination of methods is used.

Many of these methods are expensive, so that ways of minimising leachate quantity, and therefore the cost of treatment, are helpful. It is also beneficial to reduce the strength of leachate produced. For this reason, accelerating the reactions within the landfill to achieve methanogenic conditions, is desirable (Beker, 1987). The practice of leachate recirculation is becoming popular as a means of cheap leachate pretreatment, and it has also been found, in some cases, to promote the development of methanogenic conditions.(eg Beker, 1987; Stegmann and Spendlin, 1987; Boari and Mancini, 1987)

3.3 Landfill Covers

Landfill covers are used primarily to stop the emission of gases, and to stop refuse being washed or blown away from the site. They are also effective in controlling the amount of water entering the waste, and so also, the amount of leachate generated. They also usually provide a growing medium for vegetation.

Covers are usually constructed of soil, but may include a synthetic membrane. A drainage layer is sometimes provided beneath the cover to drain gas accumulating beneath the cover, or any water which does percolate through the cover.

The slope of the cover, the type of soil, and its density influence the amount of water which runs off the landfill, and the amount of water which enters the waste.

Water may be stored in the soil of the cover and later evaporate - so the thickness of the cover also influences the amount of water which eventually reaches the waste.

Covers are subject to erosion, and may also crack due to settlement of the waste, or shrinkage of materials on drying. They are, however relatively easy to inspect and repair.

Covers are the main topic under consideration in this study. A great deal more detail about covers is given in subsequent chapters.

3.4 Gas - migration; drainage; utilisation

The migration of landfill gases can pose a health hazard. Generally biogas consists of about 55%-60% methane and 40%-45% carbon dioxide. Carbon dioxide can, (at concentrations of about 10% in the air), be lethal. Methane only has an anaesthetic effect in concentrations of more than about 50% in the air. However, when it is present in air at concentrations of 5%-15% (vol), it forms an explosive mixture.(Volkmar, 1989)

Traces of toxic, carcinogenic, and odorous substances are also found in biogas. Examples of such substances are: hydrogen sulphide, mercury vapour, dichloromethane, benzole, vinyl chloride, and other halogenated hydrocarbons.(Rettenberger, 1987; Cernuschi and Guigliano, 1989)

Layers of soil cover are used to control the migration of these gases, and when the landfill is complete, a final, 'top cap' is installed. If the gas is not vented from time to time, pressure can build up beneath the cover, and the gas may escape. It may also migrate sideways, or mo·· downwards to pollute the groundwater.(Campbell, 1989)

Various systems of collecting and draining gas have been devised. Vertical wells, horizontal wells, and trenches, have been used. It is not uncommon for gas drainage layers to be included beneath the top cap.

The gas is usually pumped (rather than allowed to flow under its own pressure) from the landfill. Condensation from the gas, rising leachate levels, and the draw down of air into the landfill can be problematical in gas pumping.(Willumsen, 1987; Moss, 1987)

If biogas is extracted for safety reasons, it may be economically advantageous to use it. If used, it is usually used to power landfill operations, or small industries near the site. (Uriate, 1987; Dessaulx, 1987) The irregularity in flow rates, and calorific value of the gas, as well as the expense of installing supply pipes and gas burners, present obstacles in gas utilisation projects, so that in many cases the gas is simply flared off.

In the case of biogas utilisation projects it is beneficial to accelerate landfill reactions to reach methanogenic conditions, so as to maximise methane production. (Ham and Barlaz, 1987)

3.5 Acceleration of Reactions

In order to minimise the quantities of pollutants present in leachate, and to maximise gas production, and shorten the length of time required for a landfill to reach 'final storage quality', it is desirable to accelerate landfill reactions. To move from the aerobic to the anaerobic phase as quickly as possible is especially beneficial.

Methods of accelerating reactions include: the addition of a bacterial inoculum, such as sewage sludge; the addition of a buffer solution to raise the pH, and so create conditions conducive to methanogenic bacteria; increasing the moisture content of the waste; decreasing waste compaction; the inclusion of partially composted layers; the addition of nutrients; and leachate recirculation. (Stegmann and Spendlin, 1987; Cossu et al, 1987; Beker, 1987; Leuschner, 1987)

Unfortunately several of these methods have other undesirable effects, such as increasing the volume of leachate produced, and increasing settlement of the landfill.

Ideally, an optimal point, where leachate production can be kept to a minimum, bu methanogenic reactions can still proceed at an acceptable rate and the quality of the leachate can be kept as high as possible, should be found.

3.6 Attenuation of pollutants

The landfill itself, and the land it is sited on possess some ability to attenuate pollutants. The physical processes of dilution, dispersion, and filtration, as well as the biological degradation processes, and the chemical processes of complexation and ionic pair formation, acid-base reactions, oxidation-reduction reactions, precipitation, ion-exchange, and adsorption, all act to attenuate pollutants.(eg Blight and Ball, 1989) The extent to which a lot of the chemical and physical processes will occur is governed by the properties of the strata underlying the site. Particle size distribution, clay content, cation

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4 THE ROLE OF COVERS IN LANDFILLS

Ways of dealing with the problems mentioned above need to be developed. In this project, the feasibility of designing top covers of landfills to eliminate, or minimise leachate is investigated. If this could be achieved, the need for liner, and leachate drainage systems could be obviated. Leachate treatment could also be reduced or eliminated.

Top covers need to be installed in any event, to control gases, and to rehabilitate the site. Advantage should be taken of their capacity to limit infiltration of water into the waste. Relying on top covers, rather than bottom liners for leachate control also has the advantage that damage is easier to repair.

The advantages of allowing the waste to decompose are recognised. If a point, at which no leachate is generated, yet decomposition still proceeds, can be attained, an ideal situation will exist.

The idea of using top covers to minimize leachate production revolves around the 'water-balance' principle, and the ability of top covers to alter this balance. Covers are discussed in greater detail in the next chapter, and the water balance is discussed in detail in Chapters 3, 4, 5, and 6.

CHAPTER 2

LANDFILL COVERS - CURRENT PRACTICE

The detailed discussion of the water balance of landfills, in Chapters 3, 4, 5, and 6, will show that apart from climatic considerations, it is landfill covers that play the most important role in regulating leachate production. Covers form the first line of defence against infiltration, and also act as temporary stores, from which water may be drawn up by evaporative gradients, so limiting the production of leachate.

The focus of this study is the role of covers in the water balance of landfills. For this reason, cover design is discussed in some detail in this chapter.

1 PURPOSES OF, AND DESIGN CRITERIA FOR COVERS

1.1 Purposes of Covers

Although the minimisation of leachate generation is a very important aspect of cover performance, covers are used to achieve other goals in addition to this one. Their role in the water balance should be to:

- encourage runoff
- limit infiltration into the waste
- encourage evapotranspiration

They are also required to control health risks, and for aesthetic reasons. Their purpose in relation to these goals is to:

- control movement of gases and associated odours generated by the waste body
- reduce fire hazards
- control 'disease vectors'
- achieve anaerobic conditions within the landfill

- render the disposal site aesthetically acceptable by providing a growing medium for vegetation
- prevent waste from being washed or blown away

To achieve these aims it is desirable that the landfill be covered every day while it is being operated, by a temporary, or intermediate cover. The final cover should be placed as soon as possible. The practice of operating a landfill in 'cells' facilitates the attainment of this objective.

1.2 Design Parameters for Final Cover

A cover design should achieve all the aims mentioned above in the most economic manner. In order to accomplish this, the design should optimise a number of parameters. The optimisation of some of these parameters is discussed below.

Slope of cover: A steeper slope on the cover should encourage runoff. Slopes that are too steep however, are not aesthetically pleasing. Steep slopes are more susceptible to erosion, and reduce the overall refuse storage capacity of the landfill. Very steep slopes are difficult to vegetate. In grading a final cover, the fact that the landfill body will settle as it decomposes should be taken into account. The US EPA advises that on properly compacted fills, settlements may be taken to be in the order of 15%, while on sites where compaction control is poor, settlement may be as high as 50%. (EPA/625/4-89/022, 1989)

Type of cover material: The most cost effective cover material will be the soil which is available on the disposal site. It is desirable to have a low permeability material to limit infiltration, although the soils should not be too plastic, so as to avoid desiccation cracking. The material should also be suitable as a growing medium for vegetation, and to control landfill gas migration and influx of oxygen.

Density of cover: Compaction is expensive. The smaller the compactive effort required in placing a cover, the more cost effective the cover will be. The cover should however be suitably dense to limit infiltration and gas migration, but not too dense so as to limit vegetative growth.

Thickness of cover: The thinner the cover, the less expensive it will be. Thicker covers will be more effective in limiting infiltration into the waste because they provide a larger temporary store for water which can be drawn out of the cover by evaporation later on. A thicker cover will minimise cracking due to settlement. Some allowance for loss by erosion should also be made when choosing cover thickness.

2 COVER DESIGN OPTIONS

The chosen cover design should be evaluated in terms of all the aims mentioned in section 1 above. The evaluation of the hydrological performance of covers is dealt with in detail in later chapters. The evaluation in terms of costs, gas migration control, stability, cracking, erosion resistance, and ease of construction are dealt with in numerous publications: (eg EPA/530-SW-89-047, 1989; EPA 600/2-79-165,1979; Jacobs Engineering, 1991; German Geotechnical Society for the ISSMFE,1991; EPA/625/4-89/022, 1989.)

In many cases economic considerations outweigh any other factors, especially in countries such as South Africa which have limited financial resources. The provision of waste disposal facilities in such states competes with the provision of other basic services (such as education and housing) for limited funds. The affordability of providing any cover at all is often debated. It is therefore essential to find cheap, effective cover designs.

A number of cover designs, cover materials, and their advantages and disadvantages are discussed below.

2.1 Simple Soil Covers

A simple, single layer of soil is the most cost effective type of cover. Suitable soils are usually readily available, and thus soil covers are relatively cheap and easy to install. They are also easy to repair. Material with a low permeability is preferred, to limit infiltration, however the material should not be too plastic, so as to avoid desiccation cracking. It is usually recommended that the covers are revegetated to minimise erosion.

The thickness of cover required is controlled by climate, but recommended thicknesses vary from 2 m to 0.6 m (SRK, (BC) 1989; Carra and Cossu 1990).

Soils may be treated with substances such as cement, lime, and fly-ash, to reduce permeabilities and desiccation cracking. Dispersants such as sodium chloride, tetra sodium pyrophosphate, and sodium polyphosphate have been used to decrease permeability and aid compaction. In cold climates additives may be used to reduce frost action. (EPA 600/2-79-165, 1979)

2.2 Synthetic Covers

Flexible Membranes

A wide range of synthetic flexible membrane liners is available. A number are listed by SRK (BC), (1989), and Cadwallader, (1989). Among these are:

Polyethylene
High density Polyethylene
Chlorinated Polyethylene
Chlorosulphonated polyethylene (trade name HYPALON)
Polyvinyl chloride
Butyl Rubber

Their associated advantages and disadvantages are listed as follows:

Advantages:
- Have low permeabilities (10^{-10} cm/s)
- Are said to be resistant to chemical and bacterial degradation
- Relatively easy to install

Disadvantages:

- Are relatively expensive
- Are vulnerable to ozone and ultra violet light attack
- Are susceptible to cracking and distortion at extreme temperatures
- Cannot withstand stress from heavy machinery, puncture easily
- difficult to join
- Long term performance is not yet known

Spray on Seals

A number of synthetic spray-on type seals are also available. Among these are:

- Alkyd
- Asphalt
- Concrete
- Epoxy
- Polyester
- Polysulphide
- Polyurethane
- Silicone
- Thermoplastic molten sulphur
- Vinyl

Their advantages and disadvantages are listed below.

Advantages:

- Easy application
- Easy to repair
- Puncture resistant
- Resistant to weathering and biological attack
- Low permeabilities

Disadvantages:

- Expensive
- Difficult to control thickness

2.3 Waste Materials

A number of waste materials such as milled tailings, fly ash, furnace slag and composted sewage sludge have been used for cover material. One concern associated with using such materials is that they themselves have pollution potential. (EPA 600/2-79-165, 1979)

2.4 Composite Covers

Multi-layer, composite covers are generally recommended as having the best performance. They are, however expensive. The design of multi-layered covers is discussed by Jacobs Engineering (1991), and SRK (BC), (1989), and is reviewed below.

A complex multi-layer cover is shown in Figure 2.1 below. A complex cover would have some, or all of the layers described below.

Erosion Control Layer

Erosion protection is usually provided by a vegetation layer, which is usually the most aesthetically pleasing solution as well. A gravel layer or rip-rap may also be used for erosion protection. A maximum erosion rate of 2 t/acre/year is specified by the US EPA. A thickness of between 0.6 m and 1 m is usually called for. Surface water drainage systems are also generally required.

Moisture Retention Layer

The moisture retention zone is intended to:
- retain moisture after a precipitation event, and so allow evapotranspiration to occur, and thus reduce infiltration.
- to keep the infiltration barrier moist and so limit desiccation cracking.

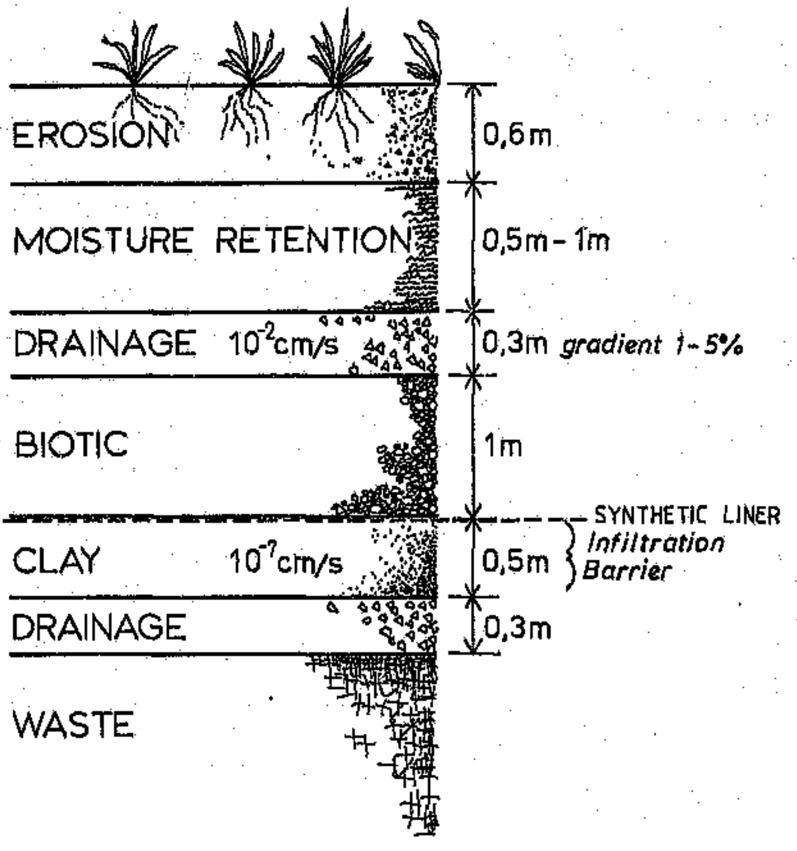

Figure 2.1
A Complex, Multi-layer Cover

Drainage/Suction Break Layer

This layer serves two purposes:

- To drain water laterally from the surface of the infiltration barrier, to limit infiltration
- To prevent moisture loss from the infiltration barrier, and so limit desiccation cracking.

A final minimum grade of between 1% and 5% (after settlement) :s recommended.

Biotic Layer

A 'biotic layer' may also be included to prevent damage of the liners by plant roots, and by burrowing animals. A 1 m thick layer of large cobblestones is usually recommended.

Infiltration Barrier

This layer consists of fine-grained soils, or synthetic material, or a combination of both. The object is that this layer should have as low a permeability as possible to inhibit infiltration. A maximum permeability of about 10^{-7}cm/s is usually specified for this layer. A mineral [illegible]er is typically required to be 0.5 m thick, while a thickness of 2 mm is generally specified for a synthetic liner.

Lower Drainage/Capillary Barrier

This layer is incorporated to drain gas. In addition it serves to reduce infiltration by maintaining a negative pore-water pressure at the base of the infiltration barrier. The required thickness of this layer is generally about 0.3 m.

The stability of multi-layered caps needs particular attention, especially where synthetic materials are used. The angle of shearing resistance between a soil layer and a synthetic membrane may be as low as 10^{0}, causing cover layers steeper than this to slide. (eg Mitchell et al, 1990)

Although composite covers feature in the literature as the most popular covers, Carra, (1990) points out that a 'typical' modern municipal landfill in the United States uses a 0.6 m thick simple soil cover.

3 SPECIFICATIONS FOR COVER DESIGN

Examples of some specifications for cover design, in use in the world at present, are given below:

3.1 South Africa

The Department of Water Affairs which is responsible for licensing waste disposal sites in South Africa, does not make any specific recommendations regarding covers. They simply ask for a report in which the sources of cover material; their distances from the site; and the availability of and suitability of cover material is discussed. They also require information regarding the quality, the thickness, and the degree of compaction of the cover, as well as the frequency at which cover will be applied. (South African Department of Water Affairs and Forestry, 1991)

3.2 International Society of Soil Mechanics and Foundation Engineering

The ISSMFE do not recommend any specific cover design, but recommend that the site be sealed and restored to the required afteruse, taking account of settlement, drainage and gas emission. They also recommend a monitoring programm (German Geotechnical Society for the ISSMFE, 1991)

3.3 The Commission of Europe... ...n

In their draft directive for landfill of waste, the Commission of European communities, require that a landfill be covered on closure, to accommodate the site to its future uses, and to integrate it into the landscape. The type of cover to be applied is not specifically recommended, but is to ... into account the types of waste deposited, and the particular characteristics of the site. (Commission of European Communities, 1991)

CHAPTER 3

INTRODUCTION TO WATER BALANCE AND SOIL MOISTURE MOVEMENT

1 THE 'WATER BALANCE' PRINCIPLE

The quantity of leachate generated by a landfill will depend on the 'water balance' of the site. According to the law of conservation of mass, the mass of water entering a system, must be equal to the sum of the masses of water leaving the system, and retained by the system. In mathematical terms:

$$IN = OUT + STORED$$

Each of the terms in this equation consists of several components.

In the case of a landfill site, the water entering the system comprises the following:

- initial water content of the refuse;
- that fraction of incident precipitation which infiltrates;
- the fraction of surface water running onto the dump, which infiltrates;
- groundwater moving into the waste body, from surrounding soils;
- water produced by chemical and biochemical reactions.

The last-mentioned component is assumed to be small and is usually neglected in water balance calculations**. Properly designed landfills should be sited such that runoff from other sub-catchments does not run onto the landfill, and groundwater does not flow into the waste. These two terms will therefore also be neglected. The relevant components of the '*IN*' term are therefore the initial water content of the refuse, *W*, and the fraction of incident precipitation which infiltrates, *I*.

$$IN = W + I$$

** This assumption is considered by some researchers to be erroneous. (Senior, pers. com., 1991) Data quantifying volumes of water produced are not easily obtainable. It is however noted that the conversion of a hydrocarbon such as glucose, under methanogenic conditions, yields only carbon dioxide and methane, and no water.

The water leaving the landfill comprises:

- evaporation;
- transpiration;
- flow of leachate through the bottom and sides of the dump;

The relevant components of the *'OUT'* term are therefore the flow of leachate from the dump, L, and evapotranspiration from the dump, ET.

$$OUT = L + ET$$

The water absorbed by, and stored in the refuse , S, represents the *'STORED'* term.

The water balance, could, therefore, be written as:

$$W + I = L + ET + S$$

By rearranging the equation in the form:

$$L = W + I - ET - S$$

the volume of leachate generated can be solved for, providing the quantities W, initial moisture content; I, infiltration; ET, evapotranspiration; and S, water stored by the refuse, are known.

The infiltration term, I, could, alternatively be expressed as net precipitation, or, precipitation, P, minus interception, C, minus runoff, R.

$$I = P - C - R$$

Hence the volume of leachate generated could be calculated according to:

$$L = W + P - C - R - ET - S$$

W, the initial moisture content of the waste makes a 'once-off' contribution to the water balance, while I, infiltration, ET, evapotranspiration, and L, leachate movement out of the waste body, occur continuously.

The water balance equation might therefore more correctly be written:

$$\Sigma L = W + \Sigma I - \Sigma ET - S$$

or

$$\Sigma L = W + \Sigma P - \Sigma C - \Sigma R - \Sigma ET - S$$

The principle of the water balance is illustrated in figure 3.1 below.

2 APPLICATIONS OF THE WATER BALANCE PRINCIPLE

The 'water balance' principle is commonly used to determine crop water requirements, groundwater recharge, water requirements of industrial processes, cities, ecological zones, and such like. It has also been used to predict quantities of leachate generated by landfill sites.

Fenn et al, 1975, describe a simple daily, or monthly moisture-budgeting procedure to predict quantities of leachate generated. Stegmann and Ehrig, 1989, compare the results of simple water balances, to the actual production of leachate from various landfills. Wiemer, 1987, discusses the effect of soil and vegetation type on the water balance of landfills. Hoeks and Ryhiner, 1987, discuss the use of clay caps to limit infiltration, and leachate production. Miller and Mishra, 1989, discuss the effectiveness of numerical models of flow through landfill caps in predicting leachate generation. Melchoir and Miehlich, 1987, examine the effects of different multi-layered caps on the water balance of landfill sites. Hojem, 1988 shows that, in areas where potential evapotranspiration exceeds precipitation, very little, or no leachate is produced by landfills.

The most simple water balance studies involve the use of general estimates of quantities of water infiltrating, evaporating, and being stored, without considering actual mechanisms of moisture movement. This can lead to wide margins of error, as found Miller and Mishra, 1989, and Hojem, 1988.

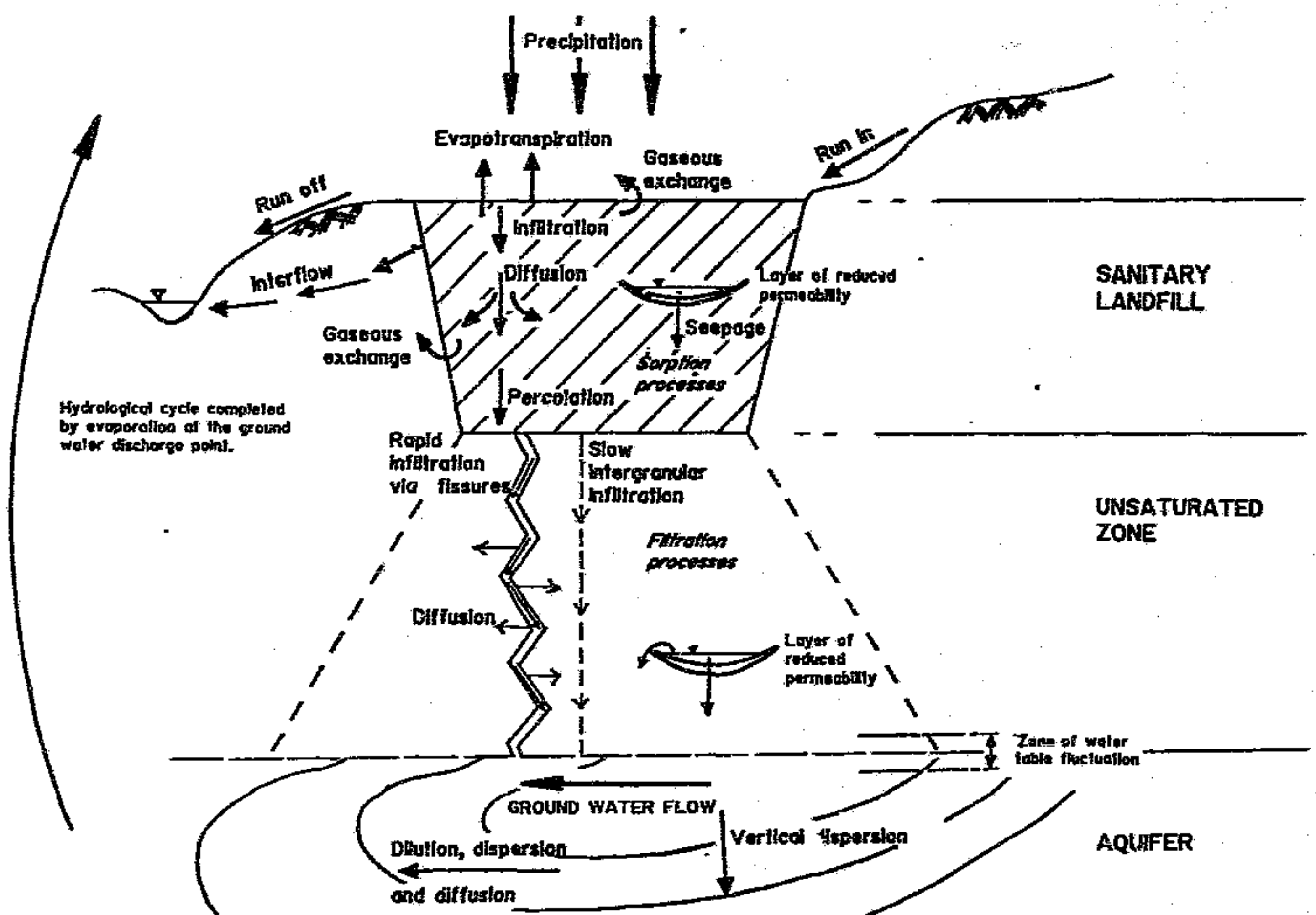

Figure 3.1
The Landfill Water Balance (after Hojem, 1988)

3 ELEMENTS OF THE WATER BALANCE

In the equation :

$$\Sigma L = W + \Sigma I - \Sigma ET - S$$

where: L is the volume of leachate generated
W is the initial moisture content
I represents infiltration
ET represents evapotranspiration
S is the water stored by the refuse

The terms, W, I, ET, and S could, conceivably be manipulated such that L becomes zero, or close to zero. In order to manipulate these terms an understanding of the processes affecting each of the terms is required. Each of these terms is discussed briefly below, and in a great deal more detail in Chapters 4, 5 and 6. Numerous comprehensive reviews on modelling the water balance have been carried out.(eg: Scholes and Savage, 1989; Holden 1991; Feddes et al. 1988; Hillel, 1980; Marshall, 1959) In addition there is abundant literature an individual aspects of the water balance.

3.1 Initial Moisture Content of Waste, W

The initial moisture content of the waste depends mostly on the composition of the waste. Paper, ash, glass, metal, plastic, have low initial moisture contents, while organics, especially food waste, and garden refuse, generally have high initial moisture contents. The initial moisture content of refuse will be highly variable. Manley et al, 1989 give estimates of the initial moisture content of refuse. Hojem, 1988 estimates the initial moisture content of compacted refuse to be 20% (w_W/w_S).

3.2 Storage, S

Little work has been done on the water storage properties of refuse. A good deal of work has, however, been done on the storage properties of soil. Numerous texts deal with this subject. (eg Jensen, 1980; Marshall, 1959; Hillel, 1980)

The behaviour of water in a granular material is affected by the size of the particles and the way in which they are arranged. Particles may be loosely or tightly packed, allowing bigger or smaller pore sizes. The pore sizes affect how strongly water is held under capillary effects within the soil.

The water storage is also affected by the nature of the individual particles. (eg the nature of the exchangeable cations of the clay minerals)

The concepts of suction, field capacity, and wilting point, which are commonly used to describe soil storage properties, are discussed below. These concepts may also be applied to refuse, since refuse is also essentially particulate in nature although the 'particles' are much larger, and are packed in a more complex manner. The nature of the individual particles is much more variable, and changes more quickly with time, as the refuse decomposes.

Suction

Energy is required to remove water from soil. The work required to move an incremental volume of water from the soil to some datum point, is known as the soil water suction. Soil water suction has two main components.

The first is termed the matric suction. Matric suction is due to the attraction of soil surfaces for water and the influence of soil pores and the curvature of the soil-water interface. (ie capillary effects)

The osmotic, or solute suction of the soil is due to the presence of solutes in the groundwater, which lower the vapour pressure of water. Solutes can move with the water, and therefore do not influence soil water flow greatly, but may be important in vapour diffusion.

As the quantity of water retained by the soil decreases, the soil suction increases, and conversely, as the moisture content of the soil increases, the soil suction decreases. Suction may therefore be used as a measure of water content.

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The relationship between suction and moisture content does, however, depend on the wetting history of the soil, since the water content - suction characteristics of a soil are hysteretic. At a given suction, a soil will contain more water during a drying cycle, than during a wetting cycle. This is illustrated in Figure 3.2

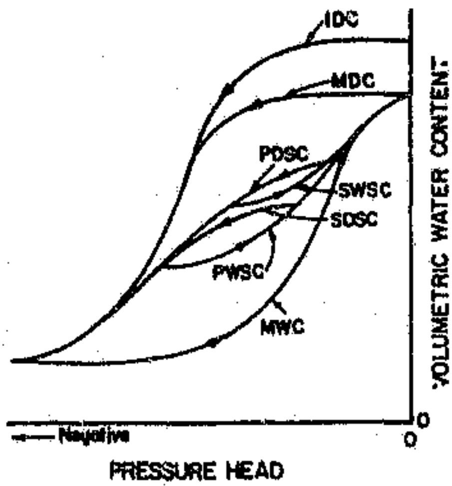

Figure 3.2
Typical Hysteresis Curves. IDC is the initial drainage curve; MWC, MDC, PWSC, PDSC, SWSC and SWDC are main, primary and secondary, wetting and drainage curves.(Gillham, 1972, cited by Jensen, 1980)

Field Capacity

The concept of 'field capacity' is often used to describing moisture storage characteristics in soil. The amount of water retained in soil which has drained for about two days (while covered to prevent evaporation) is known as the field capacity. It is not a precise quantity, but gives an approximate upper limit to the amount of water stored which may move upwards through the soil profile again. Soil may continue to drain for many days after having being wet.

Wilting Point

The permanent wilting point is the soil water content below which plants growing in that soil remain wilted. This corresponds to a suction of about 1500 kPa. Soil can be dried by evaporation to suctions much greater than this.

3.3 Infiltration, I

Infiltration may be defined as the entry of water into the soil profile. The concepts relating to infiltration are dealt with in numerous texts. (eg Jensen, 1980; Marshall, 1959, Hillel, 1980)

The infiltration capacity of the soil is an important parameter governing how much rainfall becomes runoff, and how much passes through to be stored in the soil. If water is applied at a greater rate than can infiltrate the soil, runoff and ponding will occur. The infiltration capacity of the soil at any point in time, depends on the moisture content of the soil, and will approach a constant rate as the soil approaches saturation. (The constant rate of infiltration is generally assumed to be equal to the saturated hydraulic conductivity of the soil, but is actually somewhat less, since some air remains entrapped during infiltration.) This explains why the antecedent moisture condition of a soil, as well as the rainfall intensity and duration, influence infiltration.

Other factors which influence infiltration are:

Relief: The amount of ponding that occurs will depend on the relief of the surface. Flatter surfaces with many depressions will obviously allow more ponding than will steep surfaces with no depressions. Water which ponds will partly evaporate and partly infiltrate at a later stage.

Interception: Vegetation also traps some moisture which would otherwise runoff. That portion of water which later evaporates is termed 'interception'. A portion of the water which is trapped by vegetation, later reaches the soil surface by 'throughfall' and 'stemflow'.

Surface effects: Surface effects such as sealing, as a result of raindrop impact, and crusting after dry spells, also affect infiltration. A soil surface is usually not homogeneous, and contains cracks. This is certainly true of landfill caps, where settlement of the waste, as well as shrinkage of the soil on drying, may give rise to cracking. Cracking will increase infiltration.

3.4 Evapotranspiration, ET

Evaporation takes place from plants, from soil surfaces, and from free water surfaces. A great deal of work has been done on these aspects, and is dealt with in various texts. (eg Hillel, 1980)

Evaporation from free water surfaces is not important in the water balance of landfills, since caps should be sloped so as to prevent ponding. Settlement of caps does, nevertheless, lead to the development of depressions in which water can pond. Evaporation from plants, or transpiration, does play a role in the water balance of landfills, since landfills are usually vegetated. Evaporation directly from the soil surface also occurs in the case of landfills, since at least part of the surface is bare. These terms are usually difficult to separate, so the are lumped together in 'evapotranspiration'.

The quantity of water that would evapotranspire, if there were an unlimited supply of moisture is referred to as 'potential evapotranspiration'. The water content and conductive properties of the soil, determine the rate at which water actually evapotranspires, which is usually lower than the potential rate.

In order for evapotranspiration to occur, the vapour pressure of the atmosphere must be lower than the vapour pressure at the surface of the evaporating body. For this reason, radiation and wind effects are the major influences on evapotranspiration. Radiation supplies heat required to change water into water vapour. Wind transports vapour away and so maintains relative humidity at a lower level.

Water may evaporate from upper soil layers after wetting, but is also drawn over great depths from water tables, by suction gradients, created by surface evaporation.

The presence of vegetation increases water loss from soil. Plants transmit about 90% of the water which they take up, to the atmosphere. Under conditions of moisture stress, however, transpiration is reduced.

A further source of moisture loss from landfills, is water vapour entrained in landfill gas.

4 SOIL MOISTURE MOVEMENT

The processes of infiltration and evapotranspiration interact with one another continuously, redistributing moisture, and so affect the 'water-balance' of the landfill.

Downward drainage will generally cease when gravitational and suction forces, acting downwards balance the soil suction forces acting upwards. Following downward movement of the water during drainage or redistribution, water may subsequently move upwards again under capillary effects, or as water vapour.

Layers of material of differing hydraulic conductivities may significantly affect the advance of the wetting front. If a layer of finer material is encountered, water will drain through the upper soil faster than through the fine layer, and water will acoumulate above the fine layer. If the layer is coarser than the soil above, the layer will not conduct significant amounts of water until many of the pores are filled with water. This will occur at much lower suctions than for the finer layers. When drainage starts, the coarse layer will stop conducting water at low suctions, so the water content of the layer above will remain higher. Similarly, a coarse layer will act as a capillary barrier against water moving upwards under evaporative gradients.

During drainage and redistribution water may move faster though 'macropores', or drainage paths between clods, or agglomerations of particles. Water will not, however, be drawn up through these macropores, by capillary action. Macropores will allow vapour movement.

CHAPTER 4

LITERATURE REVIEW ON QUANTIFYING INFILTRATION

The first step in quantifying infiltration is to determine precipitation. Some schemes then estimate runoff, and assume the balance infiltrates, while other schemes estimate infiltration, and assume the balance runs off. Strictly speaking, interception losses should also be taken account of, but are generally ignored. Some of the rainfall is lost to evaporation as it strikes the land surface. This effect too, is generally ignored. In this chapter, means of quantifying precipitation, runoff, interception, and infiltration are discussed.

1 PRECIPITATION

Two aspects of precipitation influence the quantity of infiltration occurring. These are the depth of rain falling, and the intensity at which the rain falls. A more intense rainfall event will result in more runoff than a less intense event, even if the total rainfall depths are equal.

1.1 Precipitation Depths

In calculating the water balance for a landfill, a prediction of what the rainfall is going to be in the future is required. The only basis that is available for making such a prediction is a record of past rainfall.

In computing water balances, it is preferable not to use average rainfall values, but realistic daily values. A very wet period within an otherwise dry spell may cause some percolation to occur, which would not be predicted if only average values are used.

Daily precipitation records for numerous widespread stations in South Africa are available from the Weather Bureau, so that data for a given site can be obtained from a nearby station. Rainfall depths and intensities can vary widely even over small distances, (Patrick, 1989) especially with the presence of orographic features. Care must therefore be exercised in choosing a representative station.

Synthetic rainfall generators are available (eg Vorster, 1991, Schroeder, 1989), but are generally only useful for the areas for which they were developed. They require data from past rainfall records for calibration. Repeating a long rainfall record successively for a number of years is a reasonable practice since it will contain data for 'wet spells' and for 'dry spells'.

It should be noted that there are errors associated with measuring rainfall, due to wind, turbulence, splash, gauge design, evaporation, and observer errors. (Scholes and Savage, 1989)

1.2 Precipitation Intensities

Autographic rainfall records are not generally available, and some assumption on rainfall intensity and duration has to be made. Even if such records were available, using the data would be difficult because of its sheer volume.

Many generalised rainfall intensity distributions have been developed, (eg Lambourne, 1990) but these usually apply to storm rainfall, (depths greater than 20 mm), and have been developed to aid stormwater runoff control design.

In the case of assessing infiltration, rainfall events of small depths are important also. Intensities during these events would tend to be lower, and therefore the percentages of infiltration would be higher.

The SCS-based storm distributions are commonly used for computing water balances. Although these were originally developed in the United States, they have been modified for South African conditions (Schmidt and Schulze, 1987) The SCS distributions have a central peak, although Schmidt and Schulze state that an initial high intensity is more common for short-duration events. The central peak gives a conservative estimate for runoff design calculations, but not for estimates of infiltration. It should also be noted that in drawing these distributions up, emphasis was placed on storms of 10 to 20 year recurrence intervals, and rainfall over 24 hour periods rather than rainfall events with low recurrence intervals, measured on a daily basis. (The Weather Bureau measures rainfall between 8:00 one day and 8:00 the next day.)

2 RUNOFF

Methods which assess runoff, without use of an estimation of infiltration, are empirical. These methods are suitable for modelling water balances on monthly, weekly, or daily bases.

2.1 Rational Method

The most simple method is the Rational method, developed in the late 1800's. It has the form :

$$Q = CIA \tag{4.1}$$

where Q is the runoff rate
I is the rainfall intensity
A is the area of the catchment
C is an empirical factor, to account for the type of runoff surface, and its slope.

This can be integrated over the duration of the storm to yield total volume of runoff. The method does not account for antecedent moisture conditions, and changing infiltration capacity. It is very simple to apply, but is known to have a great margin of error. The principle difficulty lies in assessing C. Values of C are given in many popular hydrology text books.

2.2 SCS method

The United States Soil Conservation Service developed a 'curve number' method, where the curve number takes account of the type of soil, and its condition of vegetation, and is adjusted to account for antecedent moisture conditions. Although initially developed for the United States, the method has been adapted for South African conditions (Schmidt and Schulze, 1987)

The runoff equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{4.2}$$

Where: Q is the cumulative runoff

P is the cumulative rainfall

I_a is the initial abstraction (surface storage, interception, infiltration prior to runoff)

S is the maximum potential retention given by:

$$S = \frac{1000}{CN} - 10 (inches) \tag{4.3}$$

CN is the curve number, ranging in value from 0 to 100, depending on soil type, land use, and antecedent soil moisture. Curve numbers for South African soils are given by Schmidt and Schulze, 1987.

I_a is estimated as $0.2\ S$, in the original SCS method. I_a has however been found to vary from 0.05 to 0.25 for South Africa, during different seasons. (Schulze, 1984)

The infiltration at any time is given by

$I = P - Q$ (for $I < S$)

and $I = S$ (for $I > S$)

3 INTERCEPTION

Interception is the amount of precipitation that evaporates directly from the wetted surface of the vegetation and does not reach the soil.

There are two phases in interception. The first is the build up of intercepted water until the capacity of the vegetation is full. If the shower lasts long enough, the maximum storage capacity of the vegetation is exceeded, and the second phase of interception is reached. During this phase the evaporation losses from the intercepted wate. are made up by rainfall. The increase in evaporation from intercepted water may be offset by a decrease in the saturation deficit in the atmosphere, leading to less evapotranspiration later. (Holden, 1991)

There are three basic approaches to modelling interception.

- **Average Figures:** Average figures for a particular region for a particular type of vegetation may be used. Such values have been published by de Villiers in 1975, and also by Schulze in 1984 (quoted by Holden, 1991.)

- **Regressions:** Regression equations relating interception losses to gross rainfall for different vegetation types, have been published. Holden, 1991 quotes studies carried out by Horton in 1919, and Jackson in 1975. Horton's method involved the use of Leaf A˙.˙. Indices (LAI).

- **Meteorological Models:** Sophisticated models using meteorological data and vegetation characteristics have been developed to predict interception. Scholes and Savage, 1989 quote the models of Rutter et al, and Gash as examples of these. These models require a lot of calibration data.

Interception losses may be measured, indirectly. The interception is taken to be equal to the gross rainfall less throughfall, less stemflow. Gross rainfall is measured above the canopy, throughfall is measured by troughs below the canopy, and stemflow is the water running down the plant stem to the ground. (Scholes and Savage, 1989)

4 INFILTRATION

Infiltration equations may be broadly classified as 'empirical' or 'physical'. Equations which specifically estimate infiltration are suited to modelling individual rainfall events only, and cannot be used to calculate water balances on monthly, and weekly bases. While many of these models account for the effects of antecedent moisture, and changes in infiltration capacity, most have the short-coming that they do not consider flow through cracks ('macro-pore' flow).

4.1 Empirical

These equations generally describe ponded conditions, and simply describe how infiltration capacity changes with time. They do not consider how water actually moves within soil. They assume application of water at a rate greater than, or equal to the infiltration capacity. They generally provide no mechanism for adjusting infiltration capacity under conditions where infiltration occurs at a rate below that of infiltration capacity. They also have the disadvantage that quite a lot of data are required to calibrate the equations. The more popular of these, the Kostiakov, the Horton, and the Holtan equations are described in some detail by Ward, 1981, and are briefly described below.

4.1.1 Kostiakov Equation

The Kostiakov infiltration equation was proposed in 1932, and has the form:

$$f = K_k t^{-a} \tag{4.4}$$

where: f is the infiltration capacity
t is the time from the start of infiltration
K_k } can be evaluated by fitting a straight
a } line to the data when log f is plotted against log t.

This equation implies that at high values of t, zero infiltration occurs.

4.1.2 Horton Equation

The Horton equation was advanced in 1940, and has the form:

$$f = f_c + (f_o - f_c)e^{-\beta t} \tag{4.5}$$

where: f is the infiltration capacity at time t
f_o is the infiltration capacity at time zero
f_c is the final, constant infiltration capacity
β is an empirical factor

In 1964 Betson modified Horton's equation to account for pre-ponding, interception, and partial area runoff:

$$F=a+f_cD+(f_o-f_c)(e^{-\beta mS}-e^{-\beta(D-mS)})+hR \qquad (4.6)$$

where: F is the total infiltrated volume
D is the storm duration in hours
R is the storm rainfall (inches)
f_o is the infiltration capacity at time zero
f_c is the final, constant infiltration capacity
β, a, m, h, are an empirical factors

4.1.3 Holtan's Equation

The Holtan equation was developed in 1961, and expresses infiltration capacity as a function of the storage potential of the soil in the root zone.

$$f=f_c+a(S_t-F)^b \qquad (4.7)$$

where f is the infiltration capacity
f_c is the final, constant infiltration capacity
F is the accumulated infiltration volume
S_t is the storage capacity of the root zone
a is the intercept of a log-log plot of $(f-f_c)$ versus (S_t-F)
b is the slope of a log-log plot of $(f-f_c)$ versus (S_t-F)

It has the advantage that infiltration capacity is related directly to soil moisture storage, and so can model conditions where infiltration is less than infiltration capacity.

The infiltration capacities used in all of these equations have to be measured. The empirical factors also need to be determined from experimental data. A simple way in which to measure these would be by using a double-ring infiltrometer.

4.2 Physical

The 'physical' soil flow equations attempt to describe actual flow mechanisms within the soil, under the influences of gravity and suction. Darcy studied the flow of water in homogeneous soils, in one dimension. His law has been found to hold for three dimensions also. It is, however only applicable in the range of viscous flow, where Reynolds' number is less than 2000.

$$Re=\frac{Vd}{\nu} \tag{4.8}$$

where: V is the velocity of flow
d is the dimension of the pores
ν is the kinematic viscosity of the fluid

Darcy's law describes the rate of flow as proportional to the hydraulic gradient:

$$q=-K\frac{\delta h}{\delta z} \tag{4.9}$$

where: K is the hydraulic conductivity (dependent on the properties of the flow medium, as well as the permeant
$\delta h/\delta z$ is the hydraulic gradient, the rate of change of pressure head with distance
q is the flux of water through the soil

According to the equation of continuity:

$$\frac{\delta\theta}{\delta t}=-\frac{\delta q}{\delta z} \tag{4.10}$$

where: $\delta\theta/\delta t$ is the rate of change of water content with time
$\delta q/\delta z$ is the rate of change of flux with distance

Combining equation 4.9 and equation 4.10 yields the general flow equation or Richards' equation, relating hydraulic gradient to change of water content.

$$\frac{\delta\theta}{\delta t}=\frac{\delta}{\delta z}\left(K\frac{\delta\phi}{\delta z}\right) \tag{4.11}$$

where: $\delta\theta/\delta t$ is the rate of change of water content with time
$\delta h/\delta z$ is the hydraulic gradient
K is the hydraulic conductivity

If expressed in terms of suction head, rather than hydraulic gradient, the equation has the form:

$$\frac{\delta\theta}{\delta t}=\frac{\delta}{\delta z}\left(K\frac{\delta\psi}{\delta z}\right)+\frac{\delta K}{\delta z} \tag{4.12}$$

where ψ is the suction head
and the last term accounts for the effects of gravity
$\delta\theta/\delta t$ is the rate of change of water content with time
$\delta\psi/\delta z$ is the suction gradient
K is the hydraulic conductivity

If soil moisture content θ, and suction ψ are uniquely related then the equation may be expressed as:

$$\frac{\delta\theta}{\delta t}=\frac{\delta}{\delta z}\left(D\frac{\delta\theta}{\delta z}\right)-\frac{\delta K}{\delta z} \quad OR \quad \frac{\delta\theta}{\delta t}=\frac{\delta}{\delta z}\left(\frac{K}{C}\frac{\delta\theta}{\delta z}\right)-\frac{\delta K}{\delta z} \tag{4.13}$$

where: D is the soil moisture diffusivity, $D = K\,\delta\psi/\delta\theta$
(note that D is not defined for positive heads, and that K is dependent on ψ.)
C is the specific (or differential) water capacity, $C = -\delta\theta/\delta\psi$

The evaluation of parameters, C,D, and K is discussed in detail in Chapter 6.

The physically based flow models are all based on these principles. The above equations describe one-dimensional, vertical flow, but can be modified to account for horizontal flow, and multi-dimensional flow. They consider the soil to be isotropic and homogeneous.

4.2.1 Philip's Equation

Philip developed a mathematical solution to Richards' equation in 1957. The solution is valid only for ponded conditions. (Hillel, 1980)

His solution for cumulative infiltration is:

$$I(t) = st^{\frac{1}{2}} + (A_2 + k_0)t + A_3 t^{\frac{3}{2}} + A_4 t^2 + \ldots + A_n t^{n/2} \tag{4.14}$$

And his solution for infiltration rate is:

$$i(t) = \frac{1}{2} st^{-\frac{1}{2}} + (A_2 + k_0) + \frac{3}{2} A_3 t^{\frac{1}{2}} + \ldots + \frac{n}{2} A_n t^{n/2-1} \tag{4.15}$$

where: the coefficients s, $A_2 + k_0$, $A_3,\ldots A_n$ are calculated from $K(\theta)$ and $D(\theta)$, and s is called the 'sorptivity'.

4.2.2 Green and Ampt

The Green and Ampt equation was proposed in 1911. It is developed from Darcy's law . It assumes that suction at the wetting front remains constant, and that the soil behind the wetting front is uniformly wet and of constant conductivity. It works well for initially dry soils, especially coarsely textured soils. It has been used successfully to predict infiltration from steady rain. (Hillel, 1980) It has the form:

$$f = K \frac{H_0 - H_f + L_f}{L_f} \tag{4.16}$$

where: f is the infiltration rate

H_0 is the pressure head at surface

H_f is the effective pressure head at the wetting front

L_f is the distance from surface to the wetting front

K is the hydraulic conductivity of the transmission zone

The Green and Ampt equation is popular because it is relatively easy to apply. It has the advantage that a single infiltration curve can be used for all application rates, (unlike the time dependant empirical equations.) It has the flexibility for describing infiltration under varied initial, boundary, and soil profile conditions. Equation parameters have physical significance, and can be computed from soil properties. Using field measurements, and fitting measured infiltration data does however allow for effects of heterogeneity, worm holes, crusting, etc. (Jensen, 1980)

Several researchers have made modifications to the Green and Ampt equation. The most well known modification is a two-stage form, proposed by Mein and Larson, 1973. For infiltration prior to ponding they propose the equation:

$$F_s = \frac{H_f \Delta\theta}{(I/K) - 1} \tag{4.17}$$

where: H_f is the effective pressure head at the wetting front

I is rainfall intensity

K is hydraulic conductivity

$\Delta\theta$ is the difference between initial moisture content and saturated moisture content

F_s is the infiltration volume at the time to surface ponding

Mein and Larson also suggested that the parameter H_f be evaluated as follows:

$$H_f = \int_{K_r=0}^{1} H \, dK_r \tag{4.18}$$

where: K_r is the ratio of hydraulic conductivity to saturated hydraulic conductivity

H is the pressure head at a given conductivity

4.2.3 Numerical Solutions

The Richards equation can be expressed in finite difference form. Given initial conditions, the equation can be solved to give the distribution of soil moisture within a profile, as it changes with time, and hence the amount of water which can infiltrate during a time step.

The soil data required for the solution of this equation are difficult to obtain, and most solutions ignore hysteresis.

The equation can be written in a forward difference scheme which is easy to program, but the solution becomes unstable unless the time step is kept small enough. The equation can also be written as a backward difference scheme, which leads to a set of implicit, simultaneous, nonlinear equations. Time centred, (Crank-Nicholson), and uncentered schemes may also be used. Finite difference schemes have difficulty with complex geometries of flow regions, and moving boundary conditions. Finite element schemes may also be used. (Feddes et al, 1988)

4.3 Modelling Other Effects on Infiltration

Additional effects on infiltration such as air entrapment, overland flow, sealing, crusting, and flow through macro-pores, are generally ignored in computing water balances. Attempts have, however, been made to quantify these effects. Some of this work is described below.

4.3.1 Air entrapment

As the wetting front advances, under ponded conditions air pressure of entrapped air rises, and so causes a rapid reduction in infiltration rates (which is not predicted by Richards' equation.) As air escapes, the infiltration rate rises again and approaches a constant value, which is always less than (between 30% and 90% of) the saturated hydraulic conductivity.

Morel-Seytoux and Kanji, in 1974, modified the Green and Ampt equation to account for air resistance. (Ward, 1981) Their equation is as follows:

$$f=\frac{K}{\beta L_f}(H_0+H_f+L_f) \qquad (4.19)$$

where: f is the infiltration rate

H_0 is the pressure head at surface

H_f is the effective pressure head at the wetting front

L_f is the distance from surface to the wetting front

K is the hydraulic conductivity of the transmission zone

β is a resistance correction factor between 1.1 and 1.7

It should be noted that if K is measured in the field according to correct procedures, the β term is included in K.

Other more complex relationships to describe two phase flow have also been developed. These are reviewed by Ward, (1981).

Figure 4.1 shows the effect of air entrapment on infiltration.

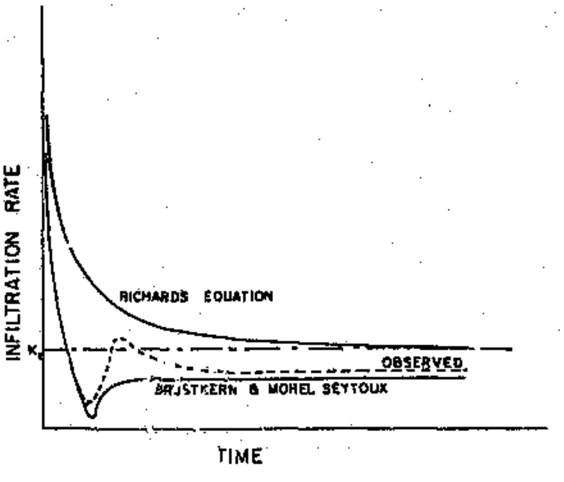

Figure 4.1
The effect of air on infiltration as predicted by solution of the Richards equation by the methods of Brustkern and Morel-Seytoux (1970), and as observed by Mc Whorter (1971) (after Jensen, 1980)

4.3.2 Adjusting ponding depth

The effects of the slope of the surface can be allowed for by appropriately adjusting the depth of ponding at the surface. This can be done by applying the 'kinematic equations'. The process is described by Akan and Yen, 1981. If such a procedure is adopted, a multi-dimensional system has to be used.

4.3.3 Sealing and Crusting

A seal or crust can develop over soils, under the beating action of raindrops, which causes soils to disperse. This effect is particularly important in sodic soils, where chemical dispersion as well as physical dispersion occurs. This chemical effect is discussed in more detail in Chapter 9.

The presence of vegetation breaks the impact of the raindrops, and so reduces their sealing effects.

The presence of a seal can greatly reduce infiltration. Reductions of up to 60% have been reported. (Ward, 1981) The effect of a crust is illustrated in figure 4.2.

Hillel and Gardner, have developed expressions to quantify infiltration into crust-topped profiles for steady infiltration, and transient infiltration. (Hillel,1980)

4.3.4 Layered Profiles

Layers of material of differing hydraulic conductivities may significantly affect the advance of the wetting front. If a layer of finer material is encountered, water will drain through the upper soil faster than through the fine layer, and water will accumulate above the fine layer. If the layer is coarser than the soil above, the layer will not conduct significant amounts of water until many of the pores are filled with water. This will occur at much lower suctions than for the finer layers. When drainage starts, the coarse layer will stop conducting water at low suctions, so the water content of the layer above will remain higher.

Finite difference solutions of the Richard's equation can deal with layered profiles. If model parameters for the Green and Ampt equation are determined by field measurements on the heterogeneous profile, these effects will be taken into account.

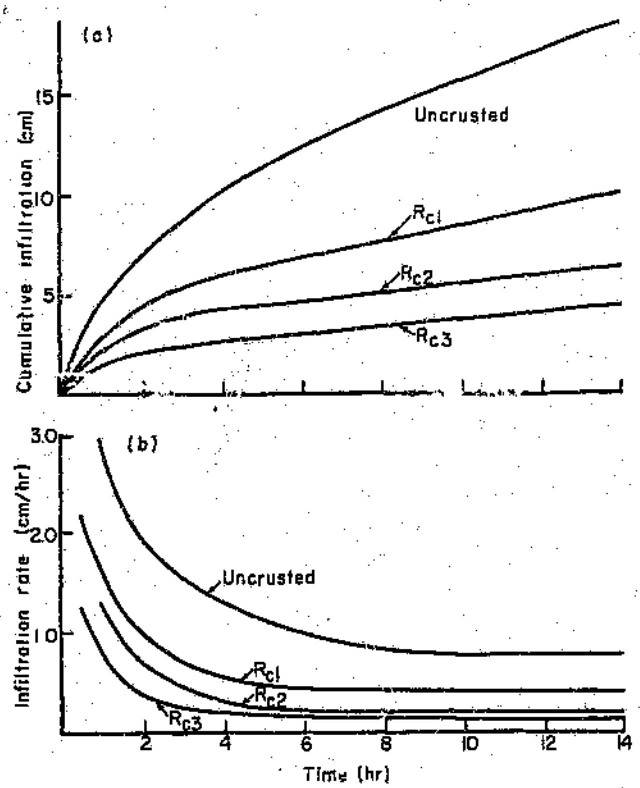

Figure 4.2
Time dependence of (a) cumulative infiltration and of (b) infiltration rate for uncrusted and crusted columns of Negev loess. (after Hillel and Gardner, 1969, cited by Hillel, 1980)

4.3.5 Preferential Flow Paths

Often part of the infiltrating water travels faster than the wetting front. Sometimes this occurs through 'macro-pores', and sometimes as a result of wetting front instability. Macropores can be caused by settlement cracks, shrinking of soil on drying, plant roots, and soil fauna, (such as termites, and earthworms.) Modelling macropore flow has been dealt with by using a 'two-domain concept' (Feddes et al, 1988). As the water moves through a macro-pore, it interacts with the water in the matrix. In numerical modelling, this water may be added to the matrix, at the bottom of the crack as a source.

CHAPTER 5

LITERATURE REVIEW ON QUANTIFYING EVAPOTRANSPIRATION

In assessing evapotranspiration, the usual approach is to first estimate the potential evapotranspiration. This figure is then adjusted for conditions where the soil moisture content is limiting, and for the effect of vegetation, giving the actual evapotranspiration.

The value of actual evapotranspiration can then be deducted from the total amount of water stored in the soil. This process of redistribution is described in more detail in chapter 6.

Methods for estimating actual evapotranspiration without first estimating the potential evapotranspiration exist, but are complex and difficult to use.

The process of evapotranspirat' n depends on the energy balance, and on the principle of conservation of mass (in this case mass of water) Many methods of assessing evapotranspiration are therefore based on determining these balances.

1 POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration is defined as evaporation from an extended surface of a green crop which fully shades the ground, exerts neglig" 'tance to the flow of water, and is always well supplied with water.(Rosenberg, Blad, a. 1983, as quoted by Scholes and Savage, 1989)

Methods for predicting potential evapotranspiration are discussed in numerous texts.(eg Scholes and Savage, 1989; Hojem, 1988; Hillel, 1980) The prediction methods may be classed as follows:

- Climatological models
- Micrometeorological methods
- Direct measurements

1.1 Climatological models

Some of the more popular climatological models are given below. They are popular because they are easy to apply, and do not require vast amounts of data. They are empirically derived. (Some of them do however, have physically-based elements.) Care should therefore be taken to apply them only to conditions which are similar to the conditions under which they were developed.

1.1.1 Thornthwaite (1948)

$$E = 1.62 \left(\frac{10\ T}{\Sigma i_j} \right)^a (cm/month) \tag{5.1}$$

where E is potential evapotranspiration

T is mean daily temperature (°C)

i is $(T_{mean}/5)^{1,514}$

and

$$a = 6.75x10^{-9}(\Sigma i_j)^3 - 7.71x10^{-7}(\Sigma i_j)^2 + 0.01792(\Sigma i_j) + 0.49239 \tag{5.2}$$

1.1.2 Blaney-Criddle (1950)

$$E = K\ \Sigma \left(\frac{tp}{100} \right) (inch/month) \tag{5.3}$$

where K is a crop constant

t is temperature (° F)

p is monthly % of daytime hours in the year

1.1.3 Linacre (1977)

$$E=\frac{700T_m/(100-A)+15(T-T_d)}{(80-T)} \tag{5.4}$$

where T is the mean temperature

$T_m = T + 0.006\,h$

h is the elevation in metres

T_d is the mean dew point

$(T - T_d) = 0.0023\,h + 0.37\,T + 0.53\,R + 0.35\,R_{ann} - 10.9$ (° C)

1.1.4 Jensen and Haise (1963)

$$E=(0.14T-0.37)R_s \tag{5.5}$$

where E is potential evapotranspiration

T is mean daily temperature (° C)

R_s is solar radiation at the top of the atmosphere

1.2 Micrometeorological methods

These models are derived from physical bases. They are relatively difficult to use because they need a lot of data which is not always easily obtainable. Simplifications have, however been made, which make them more easy to use.

1.2.1 Dalton (1802)

$$LE=(e_s-e)f(u) \tag{5.6}$$

where E is potential evapotranspiration

L is the latent heat of vaporisation of water

$f(u)$ is a shape factor

e_s is the vapour pressure at the temperature of the surface

e is the vapour pressure of the air above the surface

1.2.2 Penman (1948)

In Dalton's equation, the term e_g is difficult to assess, since the temperature of the soil surface is required. Penman used an energy balance to reduce Dalton's equation to a form for which data may be more easily measured. His equation is:

$$LE = \Delta\left[\left(R_s(1-r)(0.18+0.55\frac{n}{N})\right)-\left(\sigma T_a^4(0.56-0.09e_a^{0.5})(0.1+0.9\frac{n}{N})\right)\right] + \frac{\gamma}{\Delta}\left(0.35(1+\frac{u_2}{100})(e_s-e_a)\right)+\gamma \tag{5.7}$$

where: E is potential evapotranspiration

L is the latent heat of vaporisation of water

Δ is the slope of the saturated vapour pressure vs temperature curve at air temperature

R_s is solar radiation at the top of the atmosphere

r is the albedo

n/N is the ratio of bright sunshine to sunshine

σ is the Stefan-Boltzman constant = 2.01×10^{-9} mm Hg/d

T_a is the absolute mean daily air temperature (K)

u_2 is the mean wind velocity at 2 metres

e_d is the saturated vapour pressure at dewpoint

e_a is the actual vapour pressure at air temperature

e_s is mean saturation vapour pressure at air temperature

γ is the psychrometric constant (0.49 mm Hg/^{o}C)

Although the data for the Penman equation is theoretically more easily measured, not many weather stations measure all these parameters, so the equation is in fact rather difficult to apply. Many modified forms of Penman's equation have been proposed. One of the most well known of these being the Penman-Monteith equation (Monteith, 1965) which takes stomatal resistance of plants into account.

1.3 Direct measurements

1.3.1 Lysimeters

A soil profile is reconstructed, usually in the field, in a large container. The container is mounted on a pressure cell so that the mass balance of the profile can be measured. Provision is usually made for the collection of water percolating through the bottom of the container. This method is expensive and is not accurate, since water movement in the profile is disrupted by the base of the pan which is usually only about a metre deep. (Scholes and Savage, 1989)

1.3.2 Pan evaporation

Evaporation pans are often installed at weather stations, and so this type of data is fairly readily available. The standard pan usually used is the American 'class A pan'. The potential evaporation is taken to be equal to 0.7 times the pan evaporation. (Hojem, 1988) Inaccuracies in pan measurements can arise as a result of reading errors. Large differences in evaporation rates can be found over short distances sometimes, as a result of a change in microclimate due to relief. Care must be taken to ensure that the microclimate of the evaporation pan matches the microclimate of the site to be simulated.

2 ACTUAL EVAPOTRANSPIRATION

Although in the calculation of potential rates, evaporation and transpiration are usually lumped together (as evapotranspiration), in the assessment of actual rates, the two terms are often separated out.

Methods of evaluating actual evapotranspiration may be divided into empirically based methods and physically based methods. The physically based methods can usually be applied directly without assessing potential rates. The empirically based models are, however, easier to apply.

2.1 Physically Based Predictions

2.1.1 Actual Evaporation

The Process

Evaporation from soil takes place in three phases. The first is the 'constant rate' stage, when the soil is wet enough to supply water to the evaporation surface at a rate which matches the evaporative demand. As the soil becomes drier, it becomes less conductive, and so evaporation takes place at a rate which is lower than the evaporative demand. This is termed the 'falling rate' stage. When the soil becomes very dry, conduction of water in the liquid phase virtually ceases, but water continues to leave the soil by a process of vapour diffusion. This is termed the 'slow-rate' stage. (Hillel, 1980) Figure 5.1 illustrates the three stages. Figure 5.2 shows how the moisture diffusivity of soil decreases initially, as the soil dries, and then increases again, with further drying, when vapour movement becomes dominant. According to Feddes et al, 1988, neglecting the last stage of evaporative drying can lead to large errors, especially in arid climates.

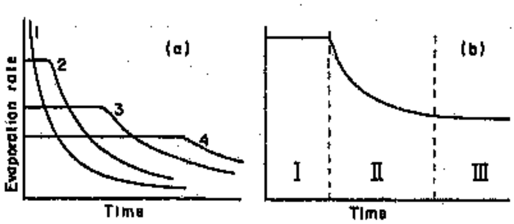

Figure 5.1
(a) Relation of evaporation rate to time under different evaporativities. (b) Relation of evaporation rate to time, indicating the three stages of the drying process. (After Hillel, 1980)

A popular belief is that evaporation from soil surfaces only takes place to depths of about 300 mm (Scholes, pers comm, 1990; Schroeder et al, 1983; Hojem, 1988.) In the case of landfills, it is commonly believed that the relatively large pores of the refuse prevent upward movement of moisture under capillary action, so that once water has passed through the cover of the landfill, it cannot be returned to the atmosphere by evaporation. (Fenn et al, 1975)

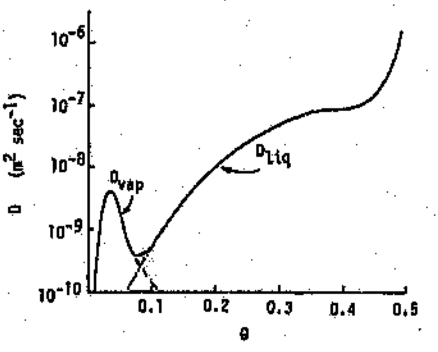

Figure 5.2
Relation between moisture diffusivity (D) and moisture content (θ) for Yolo light clay. For θ < 0.06, D includes dominant contribution in vapour phase.(Philip, 1974, cited by Hillel, 1980)

There is however, evidence to show that water moves up under evaporative gradients from far greater than 300 mm, and does indeed evaporate from refuse beneath soil covers. Blight, 1965, recorded moisture-related movements in clay at depths of 8 m . Hojem, 1988, measured seasonal changes in water content in a landfill profile to depths of about 15 m. Data given in Chapters 9 and 11 of this dissertation will add to this evidence.

Theoretical Methods of Evaluating Actual Evaporation from Soil

A number of analytical solutions of the flow equations, to evaluate evaporation from soil surfaces have been put forward (Hillel, 1980).

Fayer and Jones, 1990, use Fick's law of vapour diffusion to predict evaporation. This method accounts for movement of water through soils in the gaseous phase under non-isothermal conditions. The solution involves solving the energy balance using Fourier's law of conduction, as well as terms to account for latent heat.

Methods of Measuring Evaporation from Soil

Measurement of evaporation from the soil surface is also described by Scholes and Savage, 1989. Remote sensing techniques and lysimeters are listed as possible methods.

2.1.2 Actual Transpiration

The Process

The uptake of water by plants depends on the amount of water stored in the soil, atmospheric conditions, and the physical characteristics of the plant. (Such as the surface area of the plant leaves, and the distribution of roots within the soil.)

Computing transpiration in detail involves solving the energy balance. Energy supplied from radiation does work in extracting water from the soil, through the plant. The plant (its roots, stems, and leaves) offers resistance to flow. The resistance of leaves can change, as the extent to which the plant stomata open depends on the availability of water to the plant.

Plants are able to extract water from depths to which they send their roots, which can be up to 5 m for grass, and far greater for trees. In the case of landfills anaerobic conditions exist at shallow depths, as a result of the production of landfill gas. This gives rise to the popular assumption that plant roots can not penetrate landfill covers to depths greater than about 200 mm. Numerous examples of landfills being successfully revegetated, with large trees, do however, exist.(eg, Ettala, 1989) This would enable water to be drawn out from great depths from within a landfill.

In this study no roots were found to penetrate the cover deeper than 150 mm, on the central portion of the test landfill. Large trees are present on the slopes of the landfill. It is, however, suspected that their roots do not penetrate deeply either, because of the presence of landfill gas.

Theoretical Methods of Evaluating Actual Transpiration

The soil-plant-atmosphere system can therefore be conveniently thought of as an electrical circuit, where the atmosphere is the basic source of energy, and the roots, leaves and stems of plants are resistances. (Hillel, 1980), as shown in figure 5.3 below. The uptake of water is not usually modelled in such detail, and rougher, empirically based methods are used.

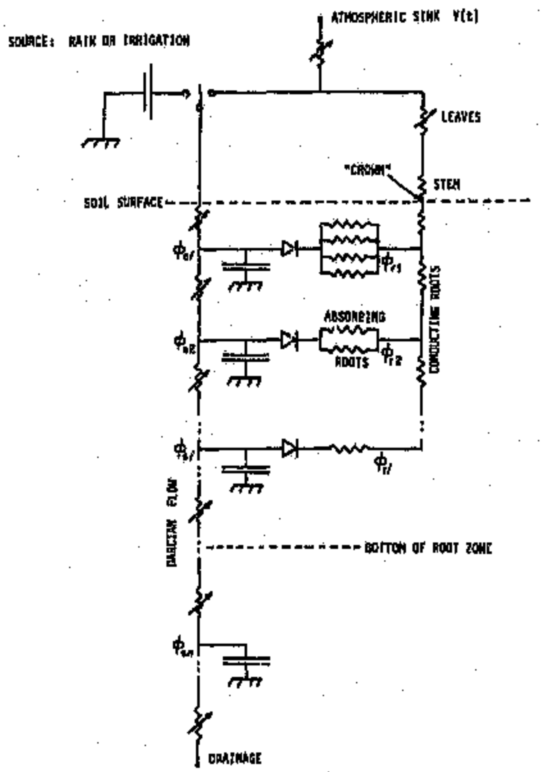

Figure 5.3

Schematic representation of a root system as a resistance network. Soil layers are shown as capacitors, linked by the variable of unsaturated vertical flow, and discharged by the roots through the variable resistance of the canopy. The roots are represented by a resistance to absorption and a resistance to conduction (the former being inversely proportional to rooting density in each layer, and the latter directly proportional to depth.) The diodes at each layer indicate one-directional flow into the roots. The atmospheric sink is shown to be of variable potential. The battery at upper left represents a source of water recharging the soil layers during episodes of rainfall.The ϕ_s, ϕ_r values indicate the potential values for water in the soil and roots, respectively, at various levels in the profile. (After Hillel, 1977, cited by Hillel, 1980)

Methods of Measuring Transpiration Rates

Measurement of actual transpiration rates include the techniques of gas analysis, lysimetry, heat pulse methods, cut shoot methods, and micrometeorological methods, described by Scholes and Savage, 1989.

2.2 Empirical Methods

These methods assume a maximum depth of evapotranspiration and empirically relate actual evapotranspiration to soil moisture content.

2.2.1 Thornthwaite and Mather

Thornthwaite and Mather developed a set of tables which relate the cumulative water deficit to the moisture content of the soil, for soil of different water holding capacities. The tables are empirically derived. The method is described in detail by Hojem, 1988.

2.2.2 Leaf Area Indices

Leaf area index methods separate soil evaporation and plant evaporation components. The leaf area index (LAI), is the ratio of leaf surface area to projected ground area beneath the canopy. For high values of LAI actual evapotranspiration may exceed potential evapotranspiration.

The ratios of transpiration to soil evaporation are related empirically by equations of the form:

$$\frac{T_p}{E_p} = C\left(1 - e^{-k(LAI)}\right) \qquad (5.8)$$

$$\frac{E_{sp}}{E_p} = C\, e^{-k(LAI)} \qquad (5.9)$$

Where: T_p is the potential transpiration rate
E_{sp} is the potential evaporation rate from the soil
E_p is the potential evapotranspiration
C and k are empirical factors

Actual transpiration and evaporation rates are commonly evaluated from empirically derived tables relating the water content of the soil, to the ratios of potential and actual evaporation and transpiration.

The potential transpiration may be distributed over the root zone,relative to the root density at each depth, providing a potential sink term. The actual sink term is then computed based on the soil water content. (eg Fayer and Jones, 1990, Schulze, 1984)

There are other factors which may affect evaporation from landfills, but which the methods discussed above do not allow for. Among these are the effect of cracking of landfill covers, the effect of heat generated by landfills during biological reactions, and the loss of water vapour entrained in landfill gas.

CHAPTER 6

LITERATURE REVIEW ON QUANTIFYING STORAGE AND REDISTRIBUTION

In this section the redistribution of soil water under the influence of suction gradients (introduced in Chapter 3) is discussed in detail. Relationships between properties such as hydraulic conductivity, water content and suction, which describe the soil moisture storage state are examined.

1 SOIL MOISTURE MOVEMENT

There are two bases on which soil water flow is commonly computed. The first is the use of the 'leaking tank' idea. The second uses solutions of the Richard's equations (as described in Chapter 4)

1.1 The 'Tank' Model

In this case the soil profile is considered to consist of several horizons, which fill with water until field capacity has been reached, and then start to drain into the next horizon. (eg Schulze, 1984; Holden, 1991) This is not realistic since water redistributes at water contents far lower than field capacity. 'Tank' models do, however, usually allow for the portion of soil water that falls between field capacity and wilting point to be drawn out by evapotranspiration, to limited depths. Simple algorithms, based on a percentage of the relative moisture contents of the profiles have been applied to redistribute water both upwards and downwards, at moisture contents less than field capacity. (Schulze, 1984)

1.2 The Flow Equations (Richard's Equation)

The Richard's equation describes the redistribution of water in the liquid phase, under the influence of suction gradients and gravity, under isothermal conditions. It assumes that water is incompressible, and that the air pressure in soils is constant. The short-comings of some of the assumptions associated with Richard's equation are discussed below.

The solution of the Richard's equation requires detailed information concerning the relationship between soil moisture content, soil suction, and hydraulic conductivity. Methods of determining these relationships are discussed in section 2 of this chapter.

1.2.1 Short-Comings of the Richards Equations

Thermal Gradients

Thermal gradients may interact with suction gradients to influence the flow of water. Soil water viscosity, and soil water diffusivity are temperature dependant. Marshall, 1959, describes how the flow of water may be influenced by thermal gradients in three different ways. These are given below.

Thermo-osmosis - Thermo-osmosis is the movement of water in films under the influence of changes in water affinity with temperature.
Thermo-capillary movements - Surface tension decreases with increasing temperature. Suction therefore also decreases with increasing temperature, so that water tends to moves from hot areas to cold areas.
Vapour movement - Water may move in soil not only as a liquid, but as a vapour also. The use of Fick's law of vapour diffusion and Fourier's law of conduction, to predict vapour movement in a soil matrix, under thermal gradients, is described by Fayer and Jones, 1990.

According to Feddes et al, 1988 , in arid and semi-arid regions, the application of simultaneous water and heat flow principles is essential to model the water balance correctly.

Landfills themselves generate heat for a number of years, due to biological reactions occurring within the waste. This may affect soil moisture movement significantly.

Air Pressure

The assumption that air pressure is constant is generally realistic under unsaturated conditions. Under ponded conditions air may be trapped and air pressure may build up. This has been dealt with in Chapter 4.

Macropores

The effects of macropores on soil moisture movement, and methods of accounting for it in solutions of the Richard's equation have been discussed in Chapter 4. Macropore flow may be very important in landfills, where covers crack extensively due to differential settlements.

Lateral flow

A one-dimensional flow model cannot predict lateral flow. Lateral flow appears to be important in landfills. (Evidence in support of this is given in Chapters 9, 11, and 13.) Richards' equation can be solved for two-dimensional flow, although it is most commonly used in its one-dimensional form.

2 SOIL MOISTURE STORAGE

The concepts of soil suction, field capacity, wilting point water content have been introduced in Chapter 3. Additional terms commonly used to describe the soil suction-moisture relationship are the residual water content and the air-entry value. The air-entry value is the suction at which soil begins to de-saturate. The residual moisture content is the moisture content which is asymptotically approached as the suction becomes very large (10 000 kPa)

The inter-relationship of these parameters is illustrated in figure 6.1 below and a description of how to evaluate these parameters follows.

The inter-relationship of hydraulic conductivity, suction and moisture content has been introduced in Chapters 3 and 4, and is discussed in further detail in this section.

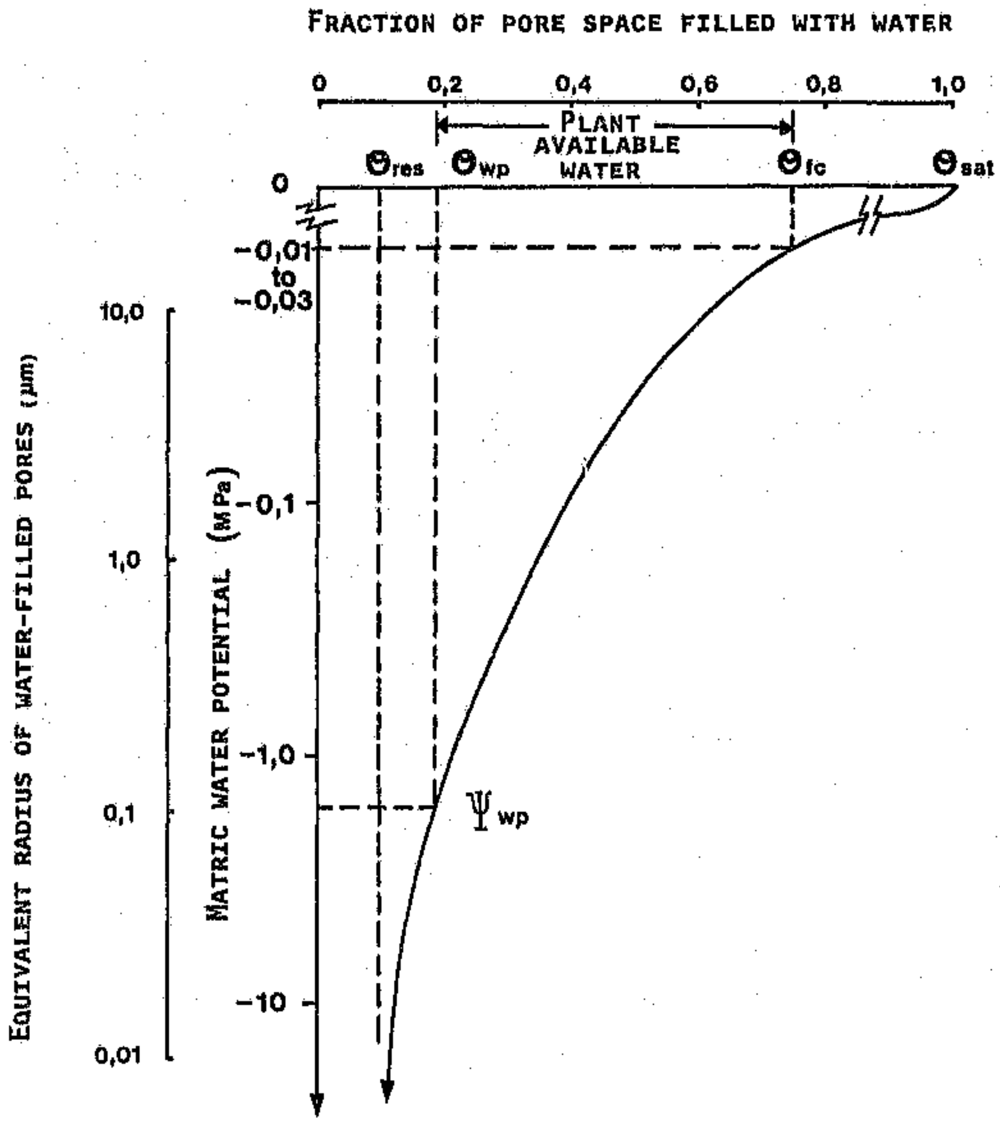

Figure 6.1

A hypothetical relationship between the water content and water potential of a clayey soil, illustrating the relationships between pore size, pore volume, residual water content, θ_{res}, water content at wilting point, θ_{wp}, field capacity, θ_{fc}, saturation, θ_{sat}, and wilting potential, ψ_{wp}. (after Scholes and Savage, 1989)

2.1 Measurement of field capacity, and wilting point

Field capacity may be measured in the laboratory as described in Appendix A. Scholes and Savage (1989) recommend applying a suction of 10 to 30 kPa, and then measuring the moisture content.

Measuring field capacity in the field entails wetting the whole profile and then determining the moisture content. (Hillel, 1980) This is very difficult to achieve, especially in areas of deep water table.

Wilting point may be determined by measuring water content after applying a suction of 1 500 kPa, or by measuring the water content at which plants do not recover from wilting.

2.2 Determination of the Retentivity Curve (Suction - Moisture Content Relationship)

In order to solve the Richard's equation, a knowledge of the water content versus suction curve (or soil water characteristic) for the soil is required. Measurements may be made in the laboratory, or the field, but are time-consuming and difficult. (Measuring in very high suction ranges is especially difficult.) A number of empirical relationships based on soil texture have been developed to describe the curves. The use of experimental or empirically derived data can be facilitated by a number of curve-fitting techniques also.

2.2.1 Laboratory Methods of Determining Suction-Water Content Curves

Pressure plates, or tension tables may be used to measure the soil moisture characteristic. This method is useful only for low suction measurements.

Pressure is applied through a porous membrane. For desorption curves, the sample starts out saturated. When the outflow of water ceases, the water content is determined gravimetrically. For low suctions the membrane may be filter paper, sintered glass, sintered bronze. For suctions of about 100 kPa, a ceramic membrane is required. For pressures of 1000 kPa a cellulose acetate film is required. For sorption curves, the soil has to be allowed to absorb water from the atmosphere whose relative humidity is controlled by a specific concentration of sulphuric acid or salts, or an imposed vacuum. (Jensen, 1980)

The suction may also be measured in laboratories using psychrometers, or filter paper.These methods may also be used in the field, and are discussed in detail in Chapter 7. Filter paper and psychrometric techniques are useful for measuring suctions in the higher ranges.

2.2.2 Regression Relationships for Determining Suction -Water Content Curves

Regression relationships relating soil-texture and bulk density ,to moisture content, at given potentials have been developed. Two of these methods are given below.

- **Rawls et al** - Rawls et al (as quoted by Everett, 1987) developed a regression relationship of the form:

$$\theta_p = a(\%\ sand) + b(\%\ silt) + c(\%\ clay) + d(\%\ organic matter) + e(bulk density) \qquad (6.1)$$

where θ_p is the volumetric water content at a given potential
a,b,c,d,e are regression coefficients

The equation holds for twelve soils between potentials of 10 kPa and 1500 kPa.

- **Hutson** - Hutson, in 1983 (quoted by Everett, 1987) developed a similar regression equation:

$$\theta_p = \beta_0 + \beta_1 Cl + \beta_2 Si + \beta_3 fSa + \beta_4 Pb \qquad (6.2)$$

where θ_p is the volumetric water content at a
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ are regression coefficients
Cl is the % clay
Si is the % silt
fSa is the % fine sand
Pb is the bulk density

2.2.3 Curve-Fitting Methods for Suction-Moisture Content Relationships

A function defining a smooth, continuous curve may be more convenient to use in numerical analyses, than is a set of tabulated data, measured in the laboratory, or obtained by theoretical methods. A number of curve-fitting techniques are used to obtain smooth curves. Some of these are discussed below.

- **Campbell** - Campbell (quoted by Everett, 1987) developed an expression relating suction to volumetric water content The differential water capacity ($d\theta/d\psi$) may also be calculated from this relationship.

$$\psi = a\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{6.3}$$

$$\frac{d\theta}{d\psi} = -\frac{\theta_s \psi^{-\left(\frac{1}{b}+1\right)}}{b a^{\frac{-1}{b}}} \tag{6.4}$$

where θ_S is the saturated volumetric water content
ψ is the suction
θ is the given water content
a,b are determined empirically

- **Hutson** - The above curve is discontinuous at $\psi = a$, or the air entry potential. Real soils do not exhibit such abrupt discontinuities. Hutson developed a two-part retentivity function. (Everett, 1987)

The point of inflection of the curve is given by:

$$\theta_i = \frac{2b\theta_s}{1+2b} \tag{6.5}$$

$$\psi_i = a\left(\frac{2b}{1+2b}\right)^{-b} \tag{6.6}$$

Between zero suction and the point of inflection, the curve is described by:

$$\theta=\theta_s-\frac{\theta_s\psi^2(1-\theta_i/\theta_s)}{a^2(\theta_i/\theta_s)^{-2b}} \tag{6.7}$$

$$\psi=\frac{a\left(1-\frac{\theta}{\theta_s}\right)^{\frac{1}{2}}\left(\frac{\theta_i}{\theta_s}\right)^{-b}}{\left(1-\frac{\theta_i}{\theta_s}\right)^{\frac{1}{2}}} \tag{6.8}$$

$$\frac{d\theta}{d\psi}=\frac{-2\theta_s\left(1-\frac{\theta_i}{\theta_s}\right)\psi}{a^2\left(\frac{\theta_i}{\theta_s}\right)^{-2b}} \tag{6.9}$$

The fitted curve is illustrated in figure 6.2

Fayer and Jones, 1990, describe four methods of fitting curves to data relating moisture content and suction, namely polynomial methods, Haverkamp functions, Brookes-Corey functions, and van Genuchten functions. These functions are described below.

- **Polynomials**

$$\theta=a+b\ \log(\psi)+c\ \log^2(\psi)+d\ \log^3(\psi)+e\ \log^4(\psi) \tag{6.10}$$

where a,b,c,d,e are regression coefficients

θ is the volumetric moisture content

ψ is the suction head

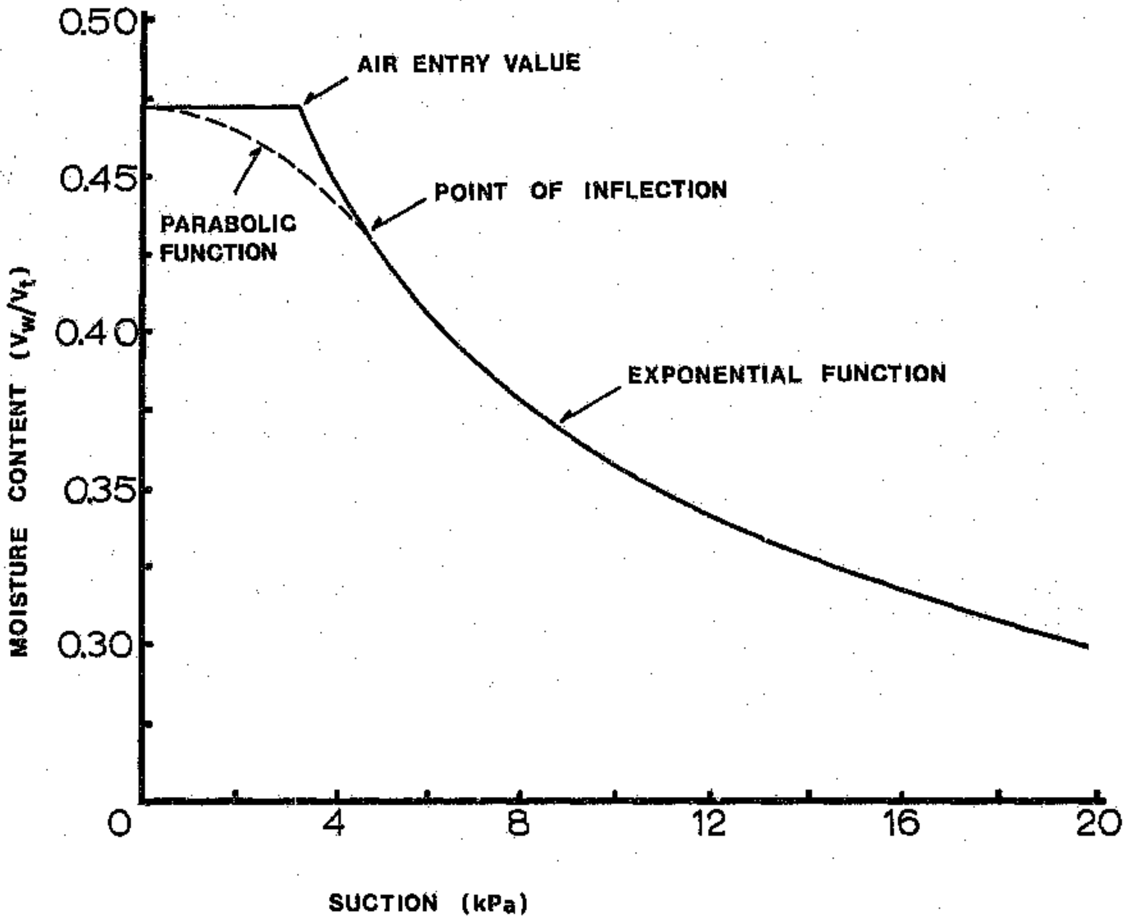

Figure 6.2
A two-part retentivity curve
(After Hutson, 1983, cited by Everett, 1987)

- **Haverkamp Functions**

$$\theta=\theta_r+\alpha\frac{(\theta_s-\theta_r)}{(\alpha+\psi^{\beta})} \tag{6.11}$$

where α,β are curve fitting parameters
θ is the volumetric moisture content
ψ is the suction head
θ_r is the residual water content
θ_s is the saturated water content

- **Brooks-Corey Functions**

$$\theta=\theta_r+(\theta_s-\theta_r)(\frac{\psi_e}{\psi})^{(\frac{1}{b})} \tag{6.12}$$

where b is a curve fitting parameter
θ is the volumetric moisture content
ψ is the suction head
ψ_e is the air entry suction head
θ_r is the residual water content
θ_s is the saturated water content

- **van Genuchten Functions**

$$\theta=\theta_r+(\theta_s-\theta_r)[1+(\alpha\psi)^n]^{-m} \tag{6.13}$$

where α,m,n are curve fitting parameters
θ is the volumetric moisture content
ψ is the suction head
θ_r is the residual water content
θ_s is the saturated water content

2.3 Determination of the Suction - Hydraulic Conductivity Relationship

2.3.1 Saturated Hydraulic Conductivity (Field and Laboratory Methods)

- **Laboratory Methods**

Hydraulic conductivity can be measured in the field using single, or double ring infiltrometers. A double ring is used in an attempt to achieve one-dimensional flow. The US EPA recommends a 12 foot square outer reservoir, and a 3 foot diameter inner reservoir, in order to obtain a representative sample area. (EPA/625/4-89, 1989)

- **Field Methods**

Conductivity can also be measured in the laboratory using a triaxial permeameter. A cell pressure and a back pressure can be applied to ensure saturation.The sample size used is small and may be unrepresentative of field conditions.

2.3.2 Unsaturated Hydraulic Conductivity (Field and Laboratory Methods)

- **Laboratory Methods**

Richards, 1965 describes a method of determining unsaturated hydraulic conductivity, using measurements from the outflow from pressure plates.

- **Field Methods**

Scholes and Savage, 1989, and Feddes et al, 1988, refer to the 'instantaneous profile method', and the method of 'plane of zero flux' as methods of determining unsaturated hydraulic conductivities in the field. They point out that these methods are very time-consuming.

2.3.3 Theoretical Calculations and Curve-Fitting for Determining Unsaturated Hydraulic Conductivities

Measuring unsaturated hydraulic conductivities is very time consuming. Theoretical and empirical methods of predicting unsaturated hydraulic conductivities which may eliminate tedious testing procedures, are discussed below.

- **Calculations based on Capillary Models**

Scholes and Savage, 1989, review calculations by Marshall, Millington and Quirk, Jackson, Mualem and Beukes, based on capillary models. Marshall, 1959 discusses hydraulic conductivity calculations, based on soil pore space.

- **Regressions based on soil-texture data**

Everett, 1987, describes how Rawls et al, in 1982 used a large database to correlate conductivity at a given degree of saturation to soil texture. Their solution was given in graphical form. Saxton et al in 1986, extended this work by providing a mathematical relationship to describe the graph:

$$K = 2.778 + 10^{-6}\{\exp[12.012 - 0.0755(\%sand) + \frac{[-3.895 + 0.03671(\%sand) - 0.1103(\%clay) + 8.7546 \times 10^{-4}(\%clay)^2]}{\theta}]\} \qquad (1.14)$$

where K is the hydraulic conductivity

θ is the given water content

- **Calculations using Water Retentivity Functions**

• ***Hutson*** divided the retentivity curve into 40 segments and summed the contribution of each pore size class to total conductivity, obtaining the relationship given below. (Everett, 1987)

$$K_s=(6.664\times10^{-5})(b^{-1.778})\left(\frac{\theta^2}{a^2}\right)\ (mm/day) \qquad (6.15)$$

$$K=K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \qquad (6.16)$$

where θ_S is the saturated volumetric water content
ψ is the suction
θ is the given water content
a,b are determined empirically
K_S is the saturated hydraulic conductivity
K is the hydraulic conductivity

Fayer and Jones, 1990, describe four methods of calculating unsaturated hydraulic conductivities, based on moisture content - suction relationships, and saturated hydraulic conductivities. These are given below.

•Polynomials

$$\log K = a+b\log(\psi)+c\log^2(\psi)+d\log^3(\psi)+e\log^4(\psi) \qquad (6.17)$$

where a,b,c,d,e are regression coefficients determined from the moisture content-suction relationship in equation 6.10
ψ is the suction head
K is the hydraulic conductivity

•Haverkamp Functions

$$K=\frac{K_s A}{A+\psi^B} \tag{6.18}$$

where A,B are curve fitting parameters based on the moisture content-suction relationship in equation 6.11

ψ is the suction head

K_s is the saturated hydraulic conductivity

K is the hydraulic conductivity

•Brooks-Corey Functions

$$K=K_s\left(\frac{\psi_e}{\psi}\right)^{\left(2+\frac{b'}{b}\right)} \tag{6.19}$$

where b is a curve fitting parameter based on the moisture content-suction relationship in equation 6.12

ψ is the suction head

ψ_e is the air entry suction head

K_s is the saturated hydraulic conductivity

K is the hydraulic conductivity

$b' = 1 + l$ (and l is the exponent of the pore-interaction term, usually = 2) (Based on Burdine's work)

OR

$b' = 2 + l$ (and l is usually = 0.5) (Based on Mualem's work) *van Genuchten Functions*

Based on Burdine's work the following expression is obtained:

$$K = K_s \frac{1-(\alpha\psi)^{n-2}[1+(\alpha\psi)^n]^{-m}}{[1+(\alpha\psi)^n]^{lm}} \tag{6.20}$$

Based on Mualem's work the following expression is obtained:

$$K = K_s \frac{[1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^n]^{-m}]^2}{[1+(\alpha\psi)^n]^{lm}} \tag{6.21}$$

where α, m, n are curve fitting parameters based on equation 6.13 above

ψ is the suction head

l is usually = 0.5 (Based on Mualem's work

OR

l is usually = 2 (Based on Burdine's work)

K_s is the saturated hydraulic conductivity

K is the hydraulic conductivity

CHAPTER 7

ASSESSING THE WATER BALANCE - BY CALCULATION & IN THE FIELD

Methods of determining individual elements of the water balance have been discussed in detail in Chapters 4, 5, and 6. This chapter deals with evaluating the water balance as a whole.

Methods of theoretically estimating the water balance abound, but the results of these computations need to be compared to the field situation in order to assess their reliability. Methods of monitoring the water balance in the field are also discussed in this chapter.

1 CALCULATING THE WATER BALANCE

Many different combinations of methods of estimating each of the various elements are possible, in computing the water balance as a whole.

The water balance can be computed in varying degrees of complexity, depending on the available data and resources, and degree of accuracy to which the balance is required to be known. Simple gross balance methods may be used, or the effects of water distribution within a profile may be taken into account. The balance may be carried out on different time scales.

Simple balance methods lend themselves to computation of water balances on monthly and weekly bases. More complex, distribution based balances lend themselves to the computation of water balances on a daily basis. The more detailed and complex the computation, the more accurate an answer one would expect to obtain.

In predicting landfill performance, the water balance of the landfill over the period for which it will continue to emit pollutants in harmful concentrations needs to be evaluated. As pointed out in Chapter 1, this could be a period of several hundred years. It is however, likely that a landfill will reach a more or less steady state with regard to water balance within a few decades. Nonetheless, to carry out water balance calculations over a period of a few decades is a tedious process, and it would be desirable to computerise even simple water balance calculations.

A number of computerised water balance models are currently available. Some have been developed specifically for waste disposal applications, (eg HELP and UNSAT-H) although there are many others which have been developed for other purposes. (eg agricultural purposes, groundwater recharge studies, water resources planning.) Numerous reviews of such models have been carried out. (eg Scholes and Savage, 1989; BC AMD Task Force, 1990; Nelson and Davis, 1987; Jacobs Engineering, 1991)

The summary review by Jacobs Engineering, 1991, of two popular models used to assess water balances of waste disposal facilities is given in table 7.1 below.

In this study the water balance of the test landfill was evaluated using the HELP model. In Chapter 12, these predictions are compared to field data, and water balance calculations carried out by Hojem, 1988.

2 EVALUATING THE WATER BALANCE IN THE FIELD

In order to assess whether existing theoretical models adequately predict the water balance for landfill sites, field measurements of the water balance have to be made. Three basic approaches to these measurements exist:

- Boreholes drilled around the site and auger holes within the landfill can be monitored to assess migration of contaminants (which act as tracers of groundwater movement)

- Lined leachate cells (or lysimeters) can be set up within the landfill and monitored

- Individual parts of the water balance (rainfall, runoff, interception, soil moisture conditions) can be measured.

In this study individual parts of the water balance were measured. Rainfall was simulated and runoff from test plots was measured. Moisture conditions within the top cap and the upper layer of refuse were also monitored. The evaluation of different possible methods for performing these tests is discussed below. Information about the actual systems used in the study, as well as the results obtained are given in Chapters 10 and 11.

Information from borehole and auger hole monitoring for the test site is also available. The results of this monitoring are discussed in Chapter 9.

	MODEL	
	HELP (Version 2)	UNSAT-H
Vertical Unsaturated Flow	Gross water balance-Darcian flow with free outflow (unit gradient), unsaturated hydraulic conductivity as function of water content (modified Brooks-Corey equation).	Numerical solution of general unsaturated flow equation, with hydraulic conductivity and matrix potential as functions of water content.
Runoff	SCS Curve method	Water in excess of what can be absorbed at the surface.
Lateral Drainage	Steady-state Boussinesq equation	None
Evapotranspiration	PET from modified Penman Equation Soil evaporation calculated from plant interception and snow accumulation Transpiration calculated from LAI given by vegetative growth and decay model	PET from Penman Equation Drying evapotranspiration calculated by Thornthwaite-Mather Method (as function of field capacity and wilting point) Vapor diffusion considered if soil surface dries out Plant roots treated as moisture sink, with root density specified by user

NOTES: Models selected from those previously applied to assessment of UMTRA Project or other DOE low-level waste disposal facilities.

Features as described in and/or inferred from model documentation.

Table 7.1
Comparative Review of HELP and UNSAT-H
(after Jacobs Engineering, 1991)

2.1 Rainfall simulation

The use of simulated rainfall, rather than natural rainfall, is preferable for carrying out runoff tests, since it is impractical to rely on the vagaries of natural rainfall. A lot more data can be collected within a given time, and specific rainfall intensities can be selected when simulated rainfall is used. Tests can be carried out at a planned time and monitoring devices can be more comfortably and easily operated in the dry.

Problems which arise in simulating rainfall however, lie in reproducing correct drop sizes, kinetic energies, drop patterns, and rain chemistry. A variety of simulators have been developed to simulate rainfall as closely as possible in drop-size, kinetic energy, terminal velocity, and drop pattern. (eg Marston, 1982; Miller, 1987; Scholes and Savage, 1989)

2.1.1 Types of Simulators

Simulators can broadly be divided into two categories; ie drip simulators, and nozzle simulators. Drip simulators are ideal for large drops, and low rainfall intensity simulations; while nozzle simulators are suitable for producing correct impact velocities, and higher intensity simulations. (Scholes and Savage, 1989)

Among the drip simulators are designs utilising hypodermic needles, capillary tubes, and lengths of yarn. (Marston, 1982). Drip simulators commonly suffer from clogging problems due to biotic growth. They are generally not easily transportable, and are therefore best suited to laboratory applications.

A variety of rotating discs, booms and moving outlets for rainfall simulators have been developed to give a non-repetitive fall pattern of drops. (Ward, 1981; Marston, 1980; Kleijn, et al., 1979)

2.1.2 Reproducing Various Intensities, Drop Sizes and Kinetic Energies

The question of what intensities of water application the simulator should be capable of delivering, to appropriately simulate rainfall is important, since the rainfall intensity affects the proportion of runoff obtained. In erosion studies it is desirable to simulate high intensity rain, since erosion takes place under such conditions. In infiltration studies however, lower rainfall intensities may be important. This aspect is discussed in greater detail in Chapter 10.

Drop size and kinetic energy may be important in infiltration studies, with regard to reproducing the sealing effects of raindrop impact.

A simulator should be capable of producing rainfall of varying intensities. Application rates of between 60 mm/h and 120 mm/h can be achieved using rotating boom instruments, while application rates of between 25 mm/h and 200 mm/h can be obtained by rotating disc instruments. (Scholes and Savage, 1989)

Drop sizes may be determined using flour tests. These tests are described by Ward, 1981.

Kinetic energies may be measured using photographic techniques. (la Grange, pers. comm., 1991)

The results of a study of drop sizes and kinetic energies for natural rainfall of different intensities are given by Marston, 1982.

2.1.3 Considerations for Field Use

An important design parameter for rainfall simulators that are to be used in the field, is portability. For this reason a lot of simulators which have been built, cover only small areas. In order to obtain a representative test area however, larger plot sizes are preferred.

2.1.4 Water Supply

Another factor limiting the size of the plots is the supply of water. Large test plots require large amounts of water for irrigation. Furthermore, the use of distilled water is preferred so as to simulate the chemistry of rain water as closely as possible. Reproducing the chemical make-up of rain water may be necessary to create the sealing phenomenon. Obtaining large quantities of distilled water is, however, difficult and expensive. The effect of the chemistry of water in rain simulation is discussed in more detail in Chapter 10.

2.2 Runoff Collection

Runoff plots are used to collect and measure all the runoff from an area of known size. Barriers are erected at the boundaries of the plots to divide the runoff from the plot from runoff from adjacent areas, and to channel the runoff to a collection/measurement point.

Scholes and Savage, 1989, report that galvanized iron channels, asbestos sheets, old conveyer belts, and concrete walls, are commonly used for this purpose.

Capturing and measuring the water running off the plots is difficult because of the large volumes that may be involved. Sample splitters can be used to reduce the volume collected, or tankless recording systems such as flume recorders, float recorders, tipping bucket gauges and flow meters may be used. (Scholes, and Savage, 1989)

2.3 Soil Moisture Measurement

An assessment of redistribution of infiltration, and the magnitude of evaporation could be obtained by monitoring soil moisture conditions. Several types of instruments for measuring in-situ water contents exist. Many of the devices actually measure soil suction, from which soil water content may be inferred. (As described in Chapter 6) Suction measuring devices should be calibrated for the particular conditions under which they are to be used. Calibration may be carried out using salt or acid solutions. The calculation of suctions of solutions is described by Gregory and Rourke, 1957.

2.3.1 **Psychrometers**

Briscoe, 1984, and Savage and Cass, 1984, describe psychrometric techniques in detail.

A psychrometer consists, basically of a thermocouple. A thermocouple comprises two lengths of wire of different metals, joined together at both ends. If the two junctions are at different temperatures, a current will flow through the loop, according to the Seebeck effect. When a current is passed through the circuit, heat is either liberated, or taken in at the junctions, (depending on the direction of current flow) according to the Peltier effect.

The Peltier effect is used to cool a thermocouple junction which is in thermal and vapour equilibrium with the surrounding medium, to below dew point temperature, causing water to condense on the junction.

Thermocouples can be used in 'psychrometric' mode, or 'dew point' mode.

In psychrometric mode, a cooling current is passed through the thermocouple for a short time, cooling the junction to below dew-point temperature, and causing water to condense on the junction. The junction then quickly warms up again, equilibrating with its surrounds, and the condensation evaporates. The temperature at which the condensation on the junction evaporates is indicated by a period during which the junction temperature remains constant, (while energy taken in is used as latent heat of evaporation.) If the dewpoint temperature is known, the relative humidity, and corresponding suction can be inferred.

In dew point mode, a cooling current which is proportional to the temperature of the junction is provided, so keeping the junction at dew point. It is easier to obtain accurate measurements using dew point mode.

Psychrometers measure total (matric plus osmotic suction.) They have the disadvantages that they are not very robust and problems with corrosion and contamination are often encountered. They operate well in the range 100 kPa to 5000 kPa. (Scholes and Savage, 1989)

A calibration exercise ca...ed out on psychrometers for this project is described in Appendix E.

2.3.2 Resistance Blocks

The electrical resistance of nylon and gypsum blocks changes with moisture content. If such a block is allowed to come to moisture equilibrium with a porous medium, the change in its resistivity can be used to measure suction.

The blocks are cheap, but are not very accurate. (± 5% for gypsum blocks, and ± 10% for nylon blocks, (Scholes and Savage, 1989)). Gypsum blocks measure in the range of 100 kPa to 4000 kPa, while nylon blocks measure in the range 0 kPa to 1500 kPa. A drawback of the blocks is that they themselves are hysteretic.

Gypsum blocks measure only matric suction.

2.3.3 Neutron Moisture Gauge

Neutron moisture [illegible] appear attractive for the continuous measurement of land[illegible] [illegible]litions, since measurements can be taken very rapidly, and with minimal disturbance of the cover material and refuse layers. Furthermore, equipment need not be left in situ, and so the risk of having equipment stolen is reduced. Measurements are reputed to be very accurate.

More detailed examination of the properties of neutron moisture gauges, however, reveals that they have severe short-comings with respect to application to landfills.

The design, operation and calibration of neutron moisture gauges is discussed in report 112, of the International Atomic Energy Agency, 1970.

A neutron gauge emits fast neutrons into the surrounding medium. The neutrons are slowed down by the medium, and the gauge then counts slow neutrons, reflected back to the source. The properties of the surrounding medium determine to what extent the neutrons are slowed, and what proportion of neutrons is reflected back to the source.

The slowing down of the neutrons is governed mainly by the presence of hydrogen atoms. The count of slow neutrons can therefore be used to deduce water contents. The manner in which the hydrogen atoms are chemically bonded, is not, however, important in the slowing down process. This means that the gauge cannot distinguish between the presence of water and the presence of organic substances, such as paper, plastic, and ash.

Provided the tested medium is relatively homogeneous, however, the gauge can be calibrated to give an accurate measurement of the moisture content of any medium, at a particular density.

In a landfill, therefore, it is not the presence of organic material which presents problems in the measurement of moisture content, by a neutron gauge, but the highly heterogeneous nature of the material.

The material of the cover of a landfill is usually relatively homogeneous. Even here, however, using a neutron moisture gauge would not give reliable answers since the cover is thin in comparison to the sphere of influence of the gauge.

The gauge gives an average reading for the material which falls within its sphere of influence. The size of the sphere of influence ranges from about 1.5 m (radius) for a soil at 0% moisture to about 0.3 m (radius) for a soil of moisture content 20%.

Calibration of neutron gauges is a tedious process, and is difficult because of the large volume of sample required.

2.3.4 Filter Paper Technique

If filter paper is allowed to come to moisture equilibrium with soil, the moisture content of the filter paper can then be measured, and the suction of the soil inferred.

If the filter paper is allowed to come into contact with the soil, the matrix suction will be measured. If there is no contact between the filter paper and the soil, total suction will be measured.

This technique can be used to measure suction in the range of 80 kPa to 6000 kPa.(Crilly et al, 1991) The method has mostly been used in the laboratory, but has also been used in the field (Crilly et al, 1991). It is cheap and relatively simple. The degree of accuracy is, however, low. Figure 7.1 shows a calibration of Whatman No. 42 filter paper, carried out by Savage et al., 1991.

A calibration of filter paper for this project is described in Appendix E.

2.3.5 Tensiometers

A tensiometer consists of a porous ceramic cup, connected to a water filled tube, and a vacuum gauge. Water moving in or out of the cup changes the suction within the tube. Tensiometers can only be used in the range 0 kPa to 80 kPa. At suctions higher than this, they leak air.

2.3.6 Other Methods

Other methods include:
- Gravimetric measurement
- Generation of acetylene gas
- Gamma ray attenuation
- Electrical capacitance
- Heat dissipation

Gravimetric measurement and measurement by generation of acetylene gas are destructive methods.

Based on the results of this literature survey of the techniques available for measuring in-situ moisture/suction conditions, (as well as economic considerations) it was decided that the techniques of psychrometry, and filter paper should be pursued in this project. The implementation of these techniques is described in Chapter 11.

2.4 Interception

Interception may be measured in the field as described in Chapter 4.

If the runoff obtained from rain of a given intensity and duration, and the interception losses are known, the quantity of infiltration can be estimated. Monitoring moisture contents will provide an estimation of the redistribution and subsequent evapotranspiration of the water which infiltrates. Tests carried out to measure parts of the water balance in this way, are described in the Chapters 10 and 11.

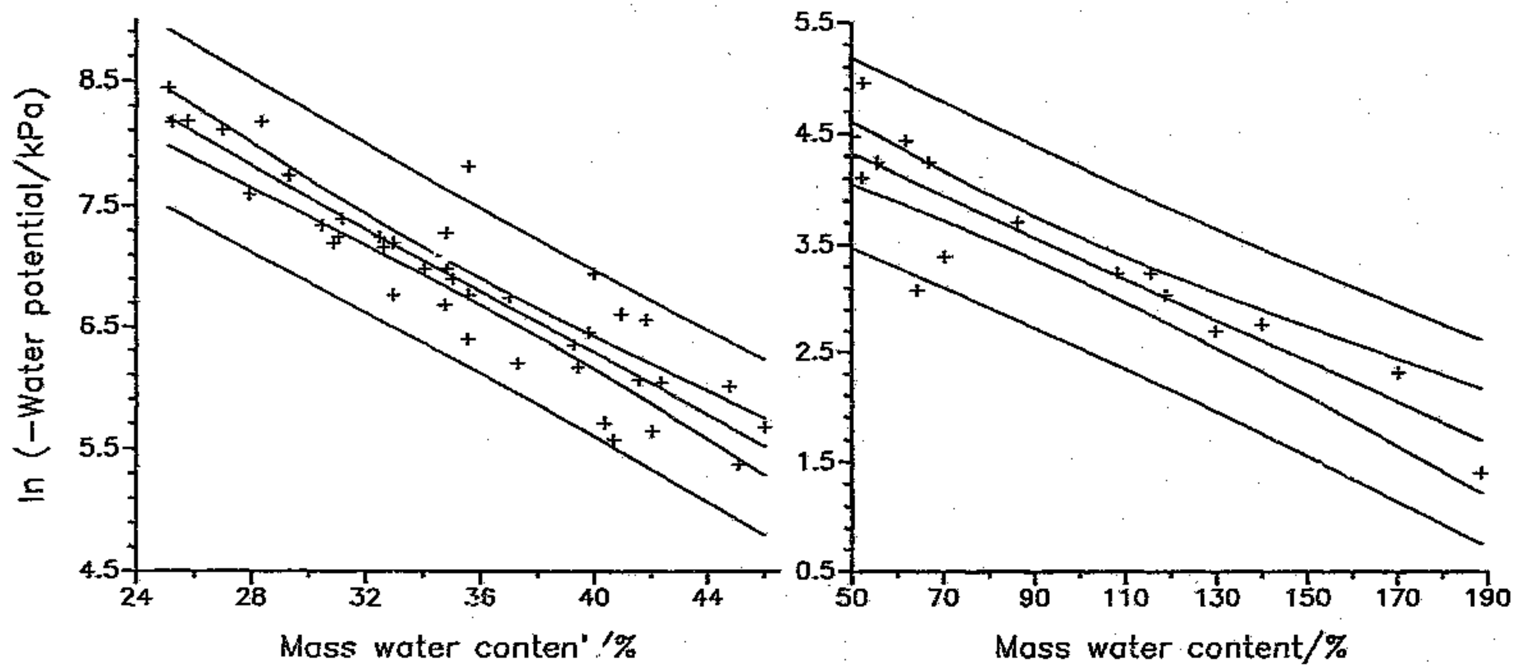

Figure 7.1
Calibration of Whatman No. 42 Filter Paper (After Savage et al, 1991)

CHAPTER 8

THE TEST SITE - LOCATION, HISTORY, & PHYSICAL PROPERTIES

In order to try and assess whether existing methods for predicting the water balance for landfills are adequate, a series of field tests were conducted. These consisted of trying to measure runoff rates, infiltration, and evapotranspiration through the upper refuse and cover layers. A series of tests to trace moisture movement within the landfill were also carried out. The tests were performed on a completed portion of one of Johannesburg Municipality's landfills. The site and its geotechnical, and geohydrological properties are discussed in this chapter.

The infiltration and in situ moisture monitoring tests themselves are discussed in Chapters 10 and 11. Moisture migration studies are discussed in Chapter 9, and predictions of leachate production, based on the properties presented in this chapter are discussed in Chapter 12.

1 LOCATION AND HISTORY OF THE SITE

The test site selected for use in this study is known as Linbro Park sanitary landfill, and is situated on the Witwatersrand. An appreciable amount of work regarding water balance and contaminant migration has already been carried out at this site by another researcher. (Hojem, 1988) This information is available as a basis on which to carry out further investigations into the water balance.

Linbro Park is situated to the north-east of Johannesburg, in Sandton. The landfill site is situated in an old borrow pit, and occupies about 70 hectares. Landfilling operations commenced in about 1969. The site presently has another 10 -15 years of life remaining, the present refuse input being about 650t per day. (Hojem, 1988; Mayne, 1990)

The refuse is placed in cells about 30 m wide and 2 m high. Layers of intermediate cover are applied daily. Some cells of the landfill have been completed. A final cover, consisting of a 600 mm thick soil layer has been installed on top of these cells, and the site has been vegetated.

The landfill is located on weathered granite, and lies above the groundwater table. Six boreholes for monitoring groundwater quality have been drilled around the site. The site is not lined, and biogas is not extracted.

Figures 8.1(a) and 8.1(b) below show the plan and section of the landfill, the position of the monitoring boreholes, and the position of the ground water table. The portion of the landfill used in the tests is indicated.

The site lies in an area of annual water deficit. (The annual potential for evapotranspiration is equal to about twice the annual precipitation. (Hojem, 1988)) These circumstances are ideal for leachate minimisation.

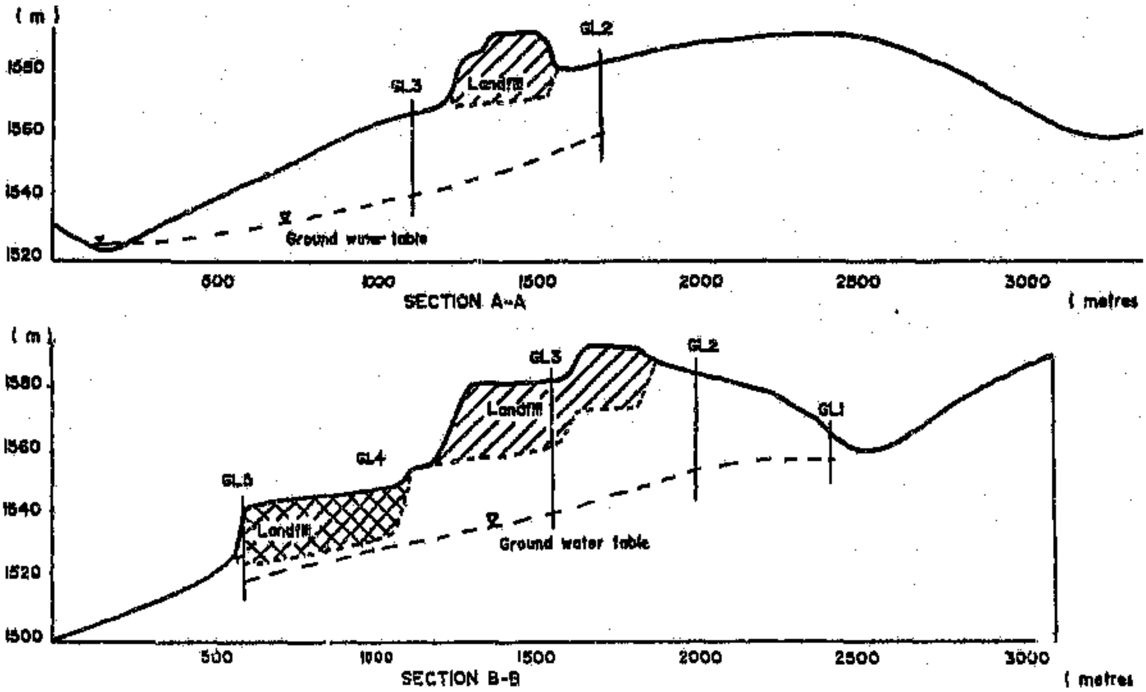

Figure 8.1 (a)
Section through Linbro Park landfill site. (Test section hatched)
(After Hojem, 1988) See p 96 for plan

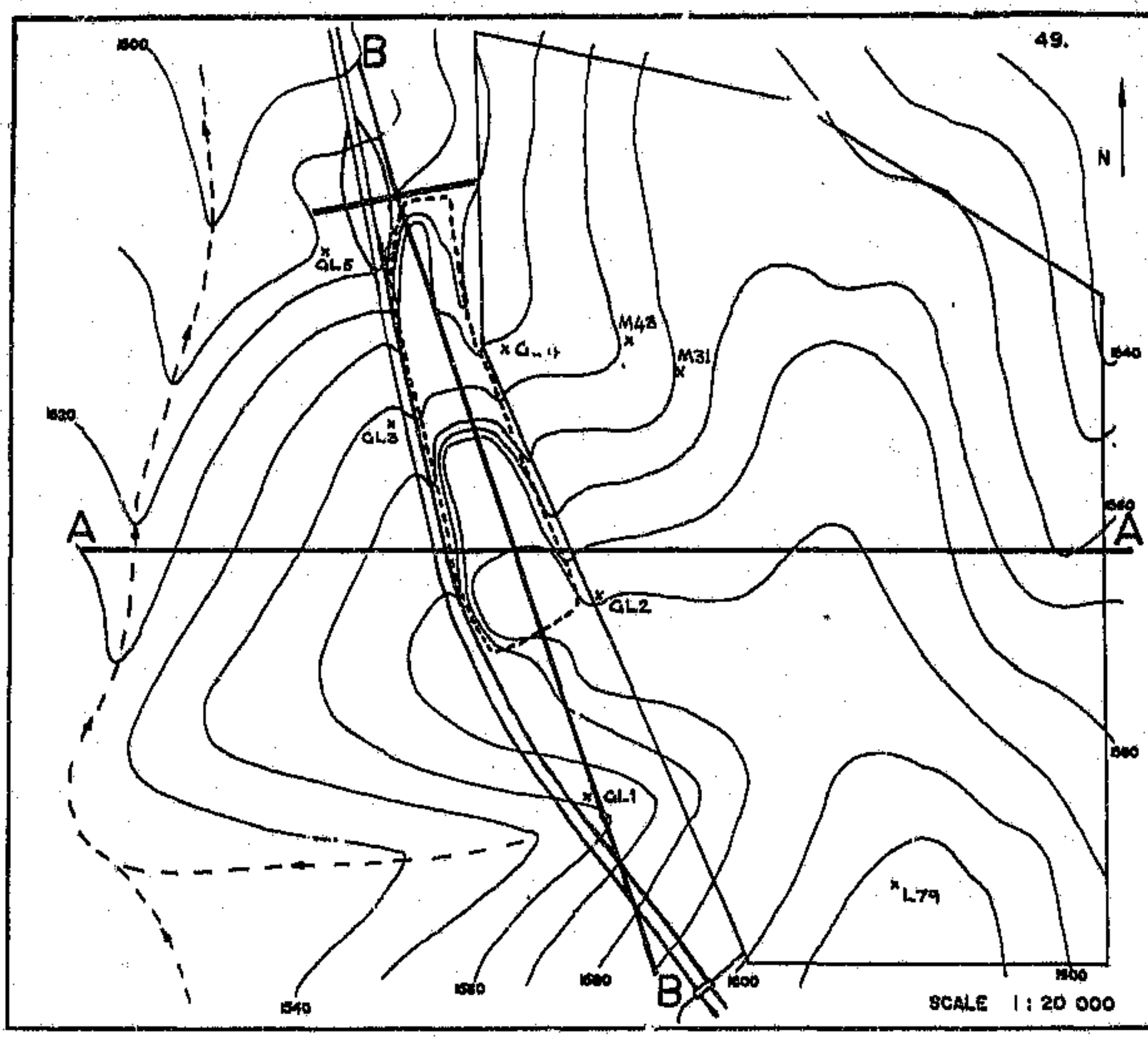

Figure 8.1 (b)
Plan of Linbro Park landfill site, showing positions of monitoring boreholes.
(After Hojem, 1988)

2 PHYSICAL PROPERTIES OF TEST SECTION

The properties of the landfill described in this section may be used in the evaluation of the water balance, in conjunction with methods described in Chapters 4, 5 and 6. Estimations of leachate production, based on these properties are discussed in Chapter 12.

2.1 Description of the Profile

The portion of the landfill used in the tests extends to a depth of about 16 m. It was completed in two phases. The lower eight metres were filled between 1970 and 1975, and the upper eight metres were filled between 1985 and 1986.

A good knowledge of the landfill profile is available. Two large diameter auger holes, spaced 120 m apart were formed in the landfill in 1987. The holes have been profiled, and their profiles are indicated in Chapter 9, figures 9.1 (a) to (k) and figures 9.2 (a) to (j).

The holes have been sampled to their full depth (some 15 m) twice: once in June 1988, (at the end of the dry season,) and again in November 1988, (at the end of the wet season). One of the holes has been sampled a third time, in July 1990 (at the end of the dry season), this time to a depth of 5 m. The samples have been subjected to various chemical and physical analyses, to try and establish the moisture distribution and migration within the profiles.

The results of the chemical analyses are discussed in Chapter 9, while the physical properties are discussed in this chapter.

2.2 Refuse Properties

Density - The refuse at Linbro Park is compacted using a landfill compactor which is capable of achieving average bulk densities of 1000kg/m^3 (Bromfield, 1991) The density of the refuse does, however, change with time as the refuse decomposes, and settles.

Field Capacity* - The field capacity of a number of samples recovered from the Linbro Park landfill site was measured in the laboratory, according to the method described in Appendix C.

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* Field capacity is measured as a water content. Water content may be expressed in a variety of ways. Geotechnical engineers commonly express moisture content on a dry mass basis. (ie, The ratio of mass of water to mass of solids, m_w/m_s) Soil physicists most commonly express moisture contents on a volumetric basis. (ie, The ratio of the volume of water in the sample to the total volume of the sample, V_w/V_t)

The measured values of field capacity for refuse samples ranged between 180% and 200% (m_w/m_s) (This would correspond to values of 65% and 70% (V_w/V_t), assuming a bulk density of 1000 kg/m^3.) Field capacity for samples of mixed refuse and soil was measured to be between 50% and 100% (m_w/m_s). (This corresponds to moisture contents of 50% to 70% (V_w/V_t).)

Hojem, 1988 quotes values of 130% to 85 % (m_w/m_s) for fresh refuse, at densities of 1000kg/m^3; (60% to 45% (V_w/V_t)) and values of 80% to 65% (m_w/m_s) for refuse aged 1 to 5 years. (45% to 40% (V_w/V_t))

HELP (Schroeder, 1989) uses a field capacity of 24% (V_w/V_t) for compacted refuse.

Table 8.1 summarises this information on field capacity.

Source	Mass Basis	Volumetric Basis
HELP	-	24%
Measured (aged refuse only)	180% - 200%	65% - 70%
Measured (refuse and soil)	50% - 100%	50% - 70%
Hojem (fresh refuse)	85% - 130%	45% - 60%
Hojem (aged refuse)	65% - 80%	40% - 45%

Table 8.1
Summary of Various Values for Field Capacity

Wilting Point and Porosity - Wilting point and porosity for these samples were not determined. HELP (Schroeder, 1989) uses values of 12% and 40% respectively for these parameters for refuse. By comparison to the majority of values of field capacity given in the table above, these figures for porosity and wilting appear to be on the low side.

Permeability - Permeability was not measured on the refuse samples which were recovered. HELP (Schroeder et al, 1983) uses a figure of 2×10^{-4} cm/s. Hojem, 1988 quotes measured values between 1.5×10^{-2} for low density refuse (500 kg/m^3) to 7×10^{-4} for high density refuse (1000 kg/m^3) No mention of the degree of isotropy which may be expected with regard to permeability is made in these references. Data presented in Chapters 9 and 11 show that lateral flow in landfills may be more dominant than vertical flow. This may be partially due to anisotropic permeablities.

Suction - Although suction measurements have been taken on the refuse, no attempt to draw up suction - moisture content curves has been made in this study. Such curves would probably vary greatly with different refuse ages, composition, and densities.

Suction is an important factor in determining the extent of bacteriological activity within the landfill. Methanogenic bacteria are active only at suctions lower than 3600 kPa, and become progressively more dormant as the suction increases beyond this. (Brits, pers comm, 1990) It is important that attempts to reduce leachate production do not inhibit bacteriological activity. Since bacteria can withstand relatively high suctions, minimising leachate production is not necessarily associated with a inhibition of decomposition.

The suctions measured in the refuse profile at the end of the dry season range from about 200 kPa to about 1000 kPa. The distribution of suction within the profile is shown in figure 8.2.

2.3 Properties of the Cover

2.3.1 General

Thickness - Numerous holes have been drilled and dug through the cover. Cover thickness has been found to vary from 1000 mm to 300 mm. On average however, it is estimated to be 600 mm thick. The cover material is decomposed granite.

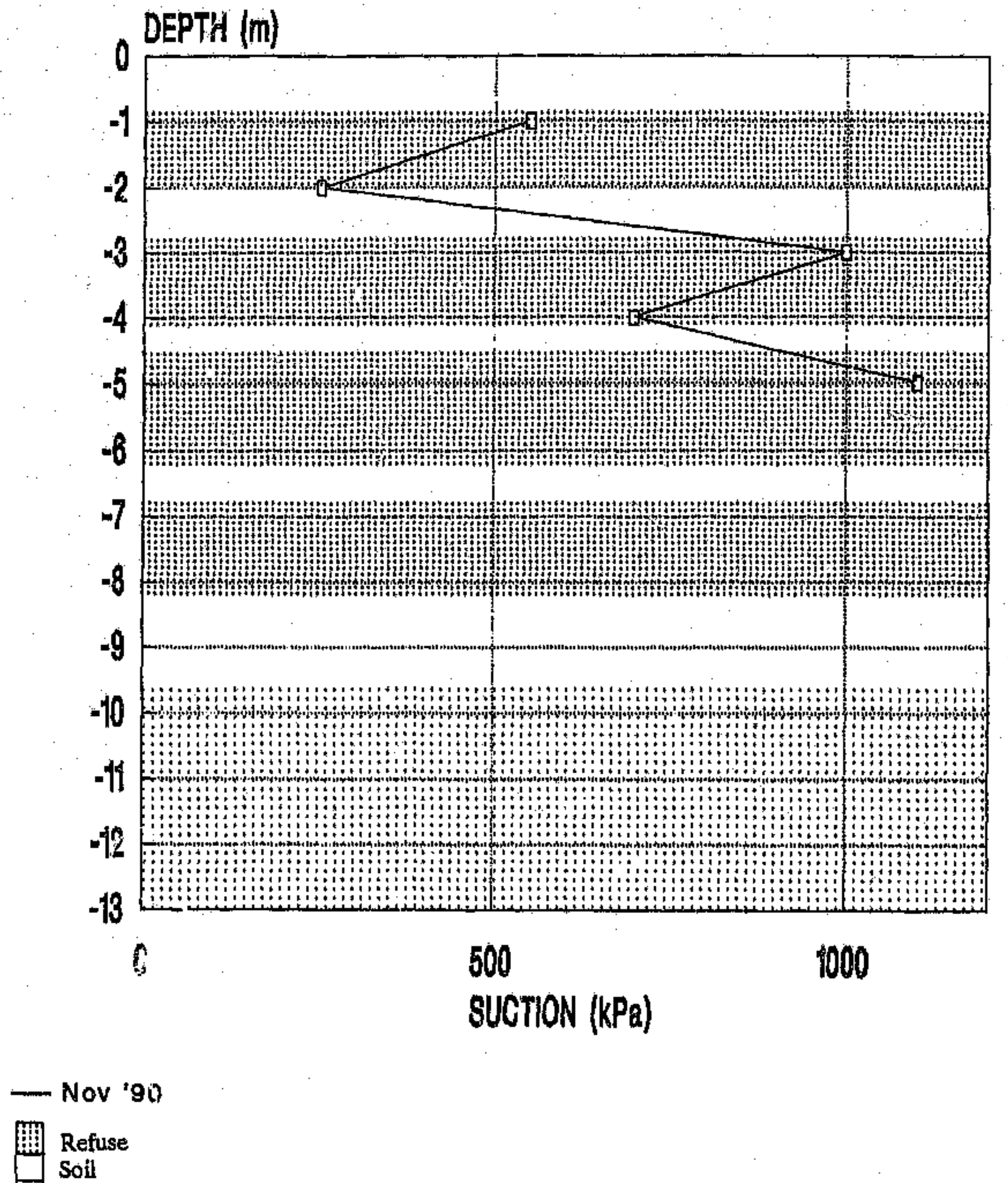


Figure 8.2
The Distibution of Suction within the South Auger Hole of Linbro Park Landfill (at the end of the dry season)

Cracking - The cover has settled and cracked extensively. Cracks up to 15 mm wide open up during the dry season. The cracks do, to some extent, close up during the wet season.

Slope - The cover has been placed so that it slopes towards the centre of the landfill, (at about 1% to 2%,) and a bund has been placed all around the edge of the landfill. Although it is preferable from a point of view of leachate generation to encourage water to run off from the site, the bund has obviously been placed in accordance with the Water Act of 1956 (Act No. 54 of 1956), which stipulates that runoff from waste dumps should be contained, and not allowed to enter surface water.

Although the cover has settled extensively, the general slope of the landfill is still towards the centre. Vegetation flourishes in localised depressions, indicating that water ponds in these areas during wet periods.

Vegetation - The cover has been vegetated with indigenous grasses. In localised areas the vegetation coverage is complete. In most areas however, the coverage is only about 50%. The site is mown at the start of the dry season, to reduce fire hazards. Numerous Black Wattle and Bluegum trees have self-seeded themselves on the lower slopes of the landfill. None of these trees grow on the central portion of the landfill, however.

2.3.2 Geotechnical and Geochemical Properties of Cover Material

Compaction - The Standard Proctor compaction curve for decomposed granite* is illustrated in figure 8.3. The results of in-situ density tests are shown in figure 8.4. These tests show that the compaction achieved ranges from about 80% to 95% of Proctor Standard maximum dry density, the compaction being higher in the upper layers of the cover.

*The tests were carried out by Mabula, 1991, on material from a site a few kilometres away, but located on the same geological formation.

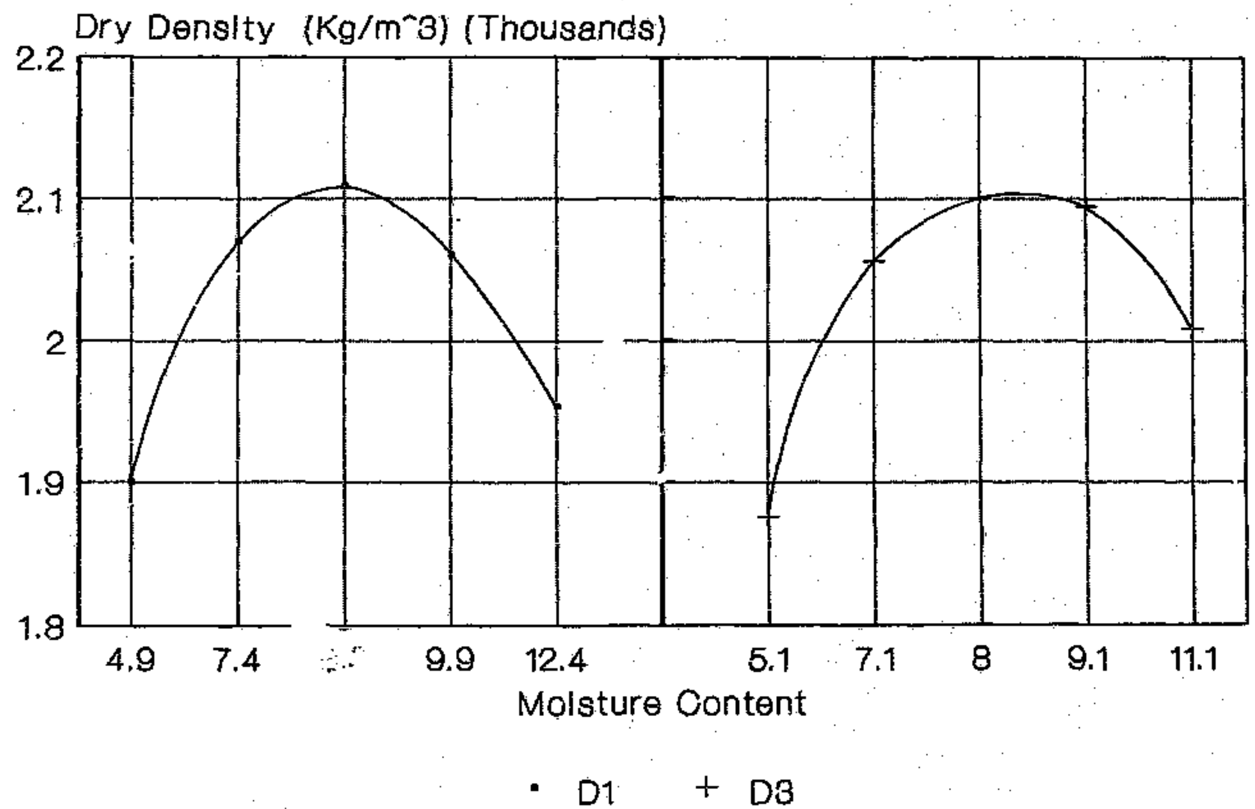


Figure 8.3
Standard Proctor Density tests for Decomposed Granite (after Mabula, 1991)

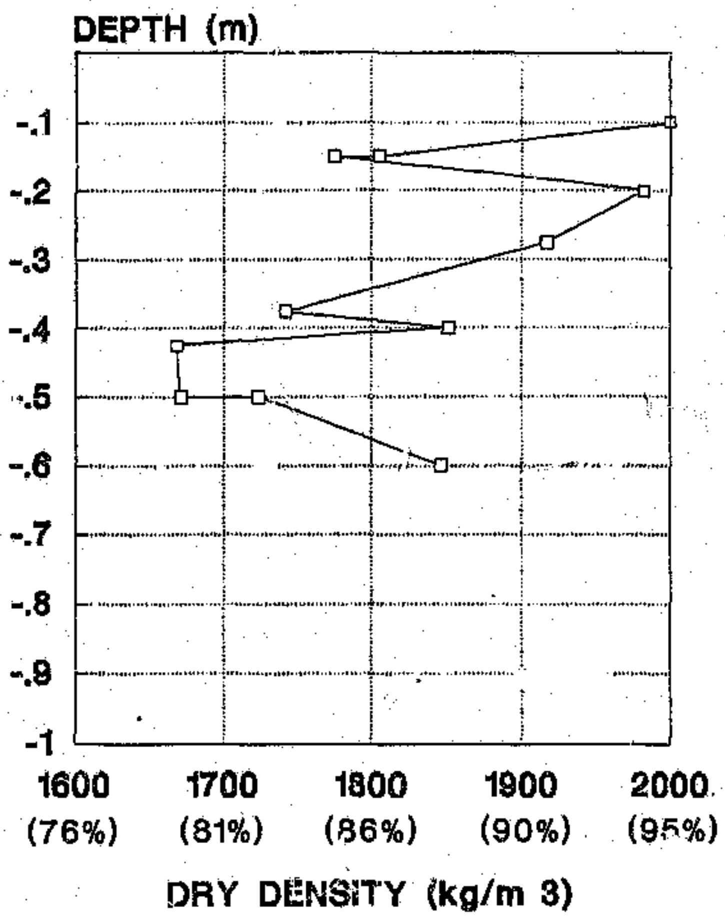


Figure 8.4
Results of in-situ density tests on Linbro Park landfill cover
(Percentages in brackets indicate corresponding percentage Proctor Standard density.)

Grading & Classification - The results of a grading analysis of the cover material are shown in figure 8.5. The values of the liquid limit and the linear shrinkage have also been determined. They are 25%, and 1.5% respectively. The plasticity of the material is low, in fact too low to carry out the test for plastic limit. The clay fraction is about 3%, and the silt fraction amounts to about 12%.

The material classifies as a clay of low plasticity (CL), on the Unified Soil Classification System (USCS), and as a sand (S) on the United States Department of Agriculture (USDA) system.

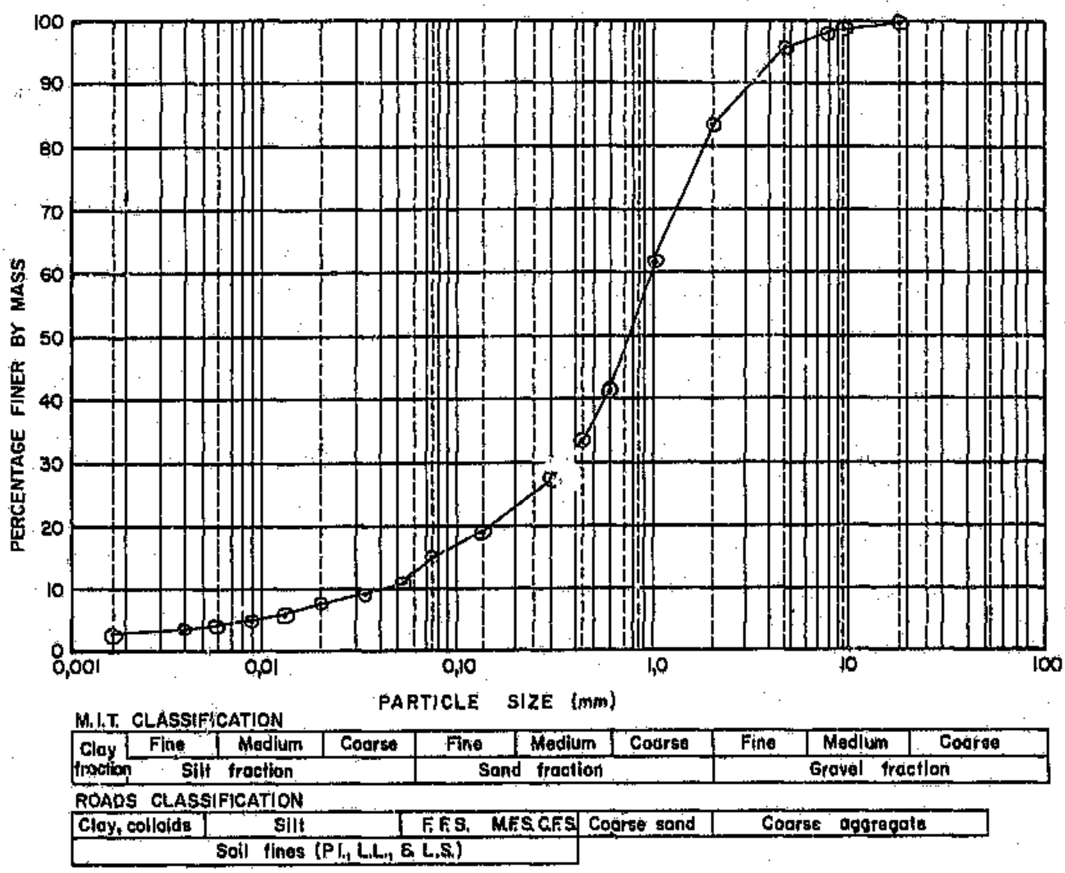


Figure 8.5
Particle Size Analysis for Cover Material at Linbro Park

Permeability - The saturated permeability of the decomposed granite has been measured using flexible wall permeameters, and small diameter samples. Sample densities varied from 95% to 100% Standard Proctor Maximum Dry Density. The values of permeability obtained range from 4 x 10^{-7} cm/s to 9 x 10^{-5} cm/s, the average being about 4 x 10^{-5} cm/s. (Mabula, 1991). HELP estimates the permeability of a CL material to be 6.4 x 10^{-5}cm/s.

Field Capacity - The field capacity of the material was determined to be between 20% and 17% (m_w/m_s) (at a dry densities of 1 700 kg/m^3 and 1 850 kg/m^3, respectively.) The corresponding water contents given on a volumetric basis (V_w/V_t) are 34% and 31.5%. HELP estimates the field capacity of material of this classification to be about 5% (V_w/V_t). There is a large discrepancy between the two values. This may be due to differences in testing methods, or may indicate that using values based on textural classifications is not at all reliable.

Porosity - The porosity of the material was determined (by oedometer test) to be 36 % (V_w/V_t) at 1 700 kg/m^3. HELP estimates the porosity of a 'CL' material to be about 35% (V_w/V_t).

Wilting Point - The wilting point (based on a suction measurement of 1 500 kPa) was found in this study to be about 14% (V_w/V_t). HELP estimates the wilting point to be 2% (V_w/V_t). Again there is a large discrepancy between the two values, indicating that using values based on textural classifications may be unreliable.

Exchangeable Sodium Percentage (ESP) - The ESP indicates the percentage of sodium ions in the soil which may be readily exchanged for other cations. This parameter is useful in determining how the permeability of the soil may change if solutions containing ions are allowed to pass through the soil. The ESP was determined to be 17,5%. This analysis was carried out by a commercial soils laboratory.

2.3.3 Suction-Moisture Content Relationship

An attempt to establish the suction-moisture content curve of the weathered granite was made. The suction of samples of different moisture content were measured, using psychrometers. Three different sets of samples were used:

- samples recovered from the field;
- specimens prepared in the laboratory (using static compaction) of dry density 1 700 kg/m^3
- specimens prepared in the laboratory (using static compaction) of dry density 1 900 kg/m^3

The laboratory specimens were prepared from initially dry material. Water was mixed with the soil until the correct water content was achieved, and the sample was then compacted.

The results are shown in figure 8.6 below. Although a very wide scatter of results was obtained, a general trend is identifiable. Some of the scatter is attributable to the limits of accuracy of the measuring instruments.* No discernible difference between the samples of different densities was evident.

Although a fair amount of geotechnical and geohydrological data is avaliable for the test landfill site, certain properties remain ill-defined. An estimation of the water balance of the landfill can nonetheless be made, using the available data.

* The accuracy of the measuring instruments was found, in a calibration exercise carried out during this project, to be about 500 kPa. Several other researchers have obtained better accuracy (eg Savage and Scholes, 1989) The calibration exercise is discussed in Appendix E.

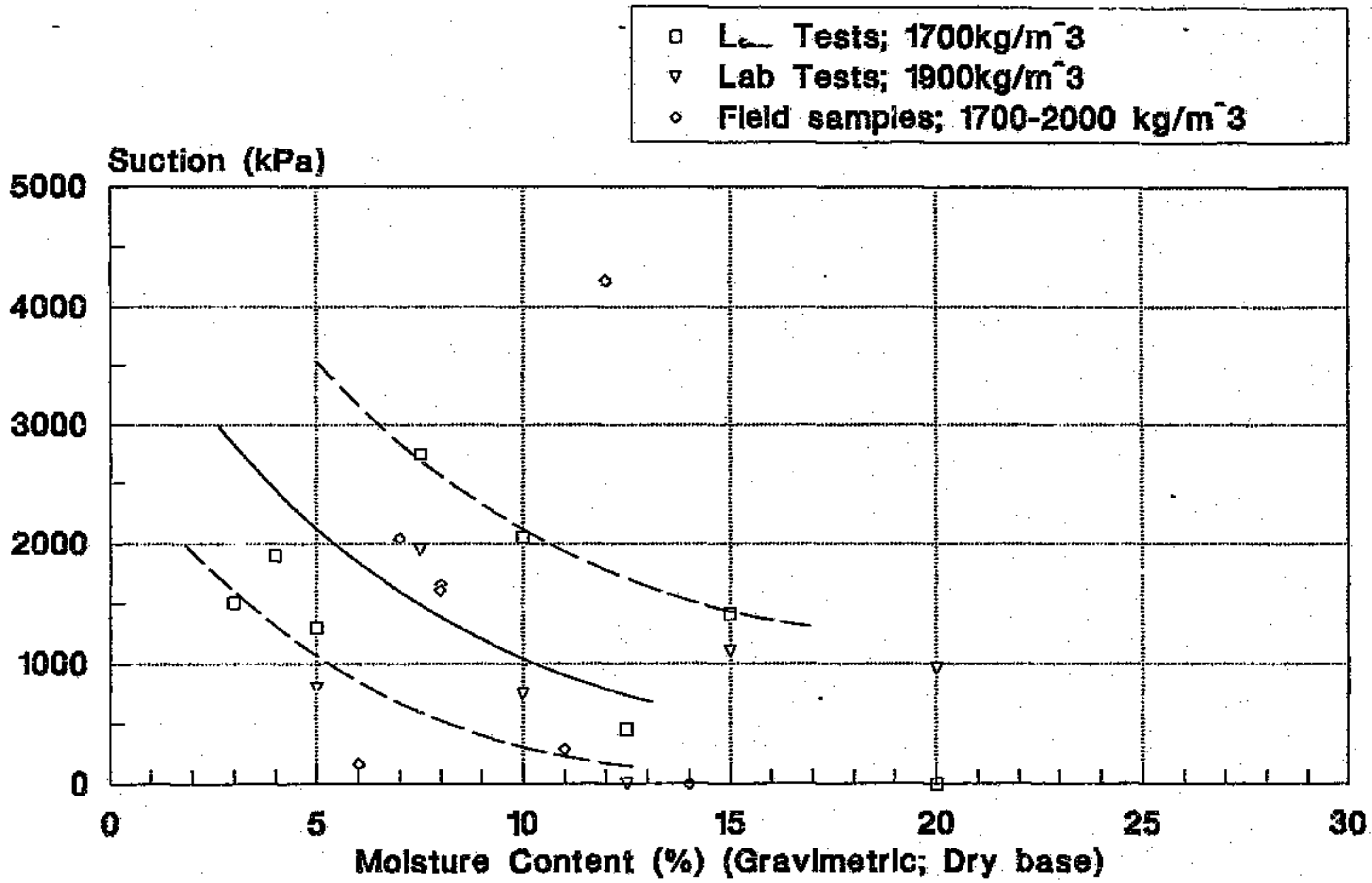


Figure 8.6
Measured suction-moisture content data for cover material from Linbro Park

CHAPTER 9

MOISTURE AND CONTAMINANT MIGRATION IN LINBRO PARK LANDFILL

In this section the results of studies of moisture and contaminant migration within the landfill are discussed. Results from monitoring boreholes, as well as results from direct sampling of the landfill are examined. These data give an indication of the state of the water balance of the landfill.

1 MONITORING BOREHOLES

The boreholes indicated in figure 8.1 (Chapter 8) are monitored by the Johannesburg Municipality. Hojem, 1988, compiled a table summarising the test results from the boreholes. The table is given below. (Table 9.1) The results indicate that leachate has not yet entered the groundwater system. Johannesburg City Council has indicated that this situation has not changed in the last three years (Mayne, pers. comm, 1991)

2 MONITORING OF AUGER HOLES

The samples recovered from the auger holes (described in chapter 8) were subjected to a number of chemical tests. The idea of this testing is to use the contaminants present in the landfill as tracers of moisture movement.

Since the moisture content of the landfill is generally way below field capacity, no leachate can be drained from the profile. Extracts of the samples are therefore made in the laboratory, and the extracts are tested. The extraction process is described in Appendix B.

The chemical parameters for which the samples were tested are listed below:

pH; chemical oxygen demand (COD); conductivity; alkalinity (as $CaCO_3$); Total Dissolved Solids (TDS); ammonia (as N); chloride (as Cl); sodium (as Na); potassium (as K); and sulphates.

BOREHOLE	DRINKING WATER STANDARDS SABS 241 (87)	GL 1 (Remote)	GL 2 (Upstream)		GL 3 (Downstream)		GL 4 (Upstream)		GL 5 (Downstream)		GL 6 (Downstream)	"TYPICAL" LEACHATE Based on averages for 63 landfills		EFFLUENT DISCHARGE STANDARDS Water Act (88)
		1983	1983	1986	1983	1986	1987	1988	1987	1988	1986	Acid phase	Methane phase	
pH	5,5 to 9,5	6,2	6,4	6,9	6,3	6,4	7,0	6,4	7,2	6,9	7,1	5,8	8,0	5,5 to 9,5
C.O.D		10	10	200	220	150	10	25	15	30	20	26575	1605	75
T.D.S		140	51	210	62	69	170	230	160	150	160	10600		
SULPHATE	600	5	5	10	5	6	16	130	16	44	18	996	269	
NITRATE	10	14	1,2	3,7	0	0,7	0	2,8	4,4	0	4,1	3,2		
NITRITE	10	0	0	0	0	0	0	0	0	0	0	0,5		
AMMONIA		0	0	0	0,7	0	6,6	1,7	2,1	1,1	0	500		10
CONDUCTIVITY	300	29	9	33	15	11	36	27	53	31	30	7175		250
ALKALINITY		40	22	140	54	47	77	28	80	59	95	4317		
HARDNESS	650	65	2	200	33	86	140	89	77	90	97	2590		
CHLORIDE	600	8	4	0	2	0	23	13	20	9	5	2000		
POTASSIUM		4	5	1,9	2	2	2,5	6	2,3	5	3	660		
SODIUM	400	16	18	15	10	19	24	13	23	18	24	1638		90+Infek

Table 9.1
Results of borehole monitoring at Linbro Park, compared to 'standards' (After Hojem, 1988)

The chemical analyses were carried out by Johannesburg's Department of Health laboratories. Four sets of tests (two on the South Auger Hole, and two on the North Auger Hole) were carried out in a previous study by Hojem, 1988. The fifth set (on the South Auger Hole) was carried out during this study. A sixth set, on the North Auger Hole was to have been carried out during this study, but difficulties experienced during sampling precluded this. The sampling for all the tests was carried out by Mr J Ball.

In addition to these tests, the samples were tested for moisture content, and the samples taken in 1990 were tested for field capacity and suction. The test procedures used to determine moisture content, field capacity, and suction are discussed in Appendices, A, C, and D respectively.

The results of these tests are indicated in figures 9.2 (a) to (k) and figures 9.3 (a) to (j). A discussion in which the results of the most recent set of tests are compared to the results of earlier tests, and information about moisture movements is deduced, follows.

Similar tests, to study the migration of contaminants have been carried out on another landfill in the Cape. (Coastal Park Landfill) The results of these tests are discussed in Chapter 13 of this dissertation.

2.1 Linbro Park South Auger Hole

Moisture Content - Figure 9.2(a) shows moisture contents in the profile at the end of the wet season 1988, and at the end of the dry season in 1988, and 1990. In November 1990, at a level of 3m a very high moisture content was recorded. This is thought to be due to an unseasonal wet spell which occurred that winter.

The field capacities for the profile, to a depth of 5m are shown. In most cases, the water content of the profile is well below field capacity. In terms of the classical concept of field capacity this would suggest that no water has yet drained from the refuse, and no leachate has therefore been produced. Indeed, the profile appears not to be transmitting moisture to the groundwater, as is shown by results obtained from the monitoring boreholes.

The fact that the entire profile wets up during the wet season, however, indicates that the moisture is transmitted down the profile at moisture contents far lower than field capacity. Conversely, the fact that the entire profile dries out during the dry season, suggests that water is drawn up by evaporative gradients from great depths. This behaviour is not contrary to Darcy's law which predicts that moisture will be transmitted from areas of lower suction to areas of higher suction, even if that suction is less than that corresponding to field capacity. The hydraulic conductivity is, however, reduced at high r ctions.

There is no reason why the movement of moisture should be primarily in the downward direction at all times, as is implied in many popular methods of computing water balance. The suction gradient due to gravity is small (10 kPa/m) in comparison to suction gradients induced by evapotranspiration

A very rough calculation of the velocity at which water is moving out of the profile (assuming one dimensional downward flow, and based on average moisture content changes during the dry season) yields a result of about 1.8 m/year. Assuming this to be correct one would expect salt concentrations found at a depth of 1 m in 1988, to be found at a depth of 5 m in 1990. Examination of chemical analyses shows this generally not to be the case, which suggests that the assumption of or dimensional downward flow is incorrect.

In the discussion of the chemical analyses which follows, more evidence to suggest that flow within a landfill is not one dimensional, is presented. This suggests that most water balance models have severe short-comings, since they consider only vertical movement.

pH - (See figure 9.2 (b)) Results of the 1988 test indicate that conditions in the landfill become more acidic during the dry season. This may be due to the fact that the decreased moisture content during the dry period creates conditions less favourable to methanogenic activity. The 1990 results show that the pH has increased during the past 2 years, indicating that methanogenic activity has become more prevalent. A corresponding decrease in COD would be expected.

COD - (See figure 9.2 (c)) As expected from the results of the pH tests, the COD within the profile has decreased between 1988 and 1990. This suggests that the landfill is entering the methanogenic phase. (The COD within the profile is still, however, high for methanogenic conditions) The drop in COD levels does not necessarily mean that organics have been transported by water from the profile. The organics may have been converted by bacteria into gases, which may have then escaped from the landfill.

TDS - (See figure 9.2 (d)) The tests conducted in 1988 show a peak concentration of TDS at about the 6m level. The concentrations of salts in the profile decreased between the wet season and the dry season of 1988, and decreased even further two years later, indicating that the contaminants have been transported away from the sampling site.

It should however be noted that there is a slight increase in the concentrations of salts near the surface, at the end of the dry season. This indicates an upward movement of moisture, under evaporative gradients.

The concentrations given in figure 9.2 (d) are shown as mg TDS/kg dry solids. If one considers that the moisture content of the entire profile has decreased, the decrease in TDS might be due to the decreased water content. (ie The concentration of TDS within the water held by the refuse may not have changed.) The results were re-evaluated as mg TDS/ kg water present in the refuse. The results are shown in figure 9.2 (k).

The concentrations of TDS in the water contained in profile are fairly similar at the end of the wet and dry seasons of 1988. The concentration was found to have decreased by the end of the dry season, 1990. This indicates that the water moving out of the profile, is to a large extent taking salts with it - which suggests that not all the water leaving this part of the profile is evaporating. Peak concentrations of TDS have not moved downward as far as calculations based on the assumption of one dimensional downward movement suggests. This implies that flow from the profile may be lateral.

Conductivity - (See figure 9.2 (e)) Although the change in concentration of TDS within the profile has been appreciable, between the three dates of sampling, conductivity has shown very little change.

Alkalinity - (See figure 9.2 (f)) Alkalinity shows very much the same pattern as the TDS. The peak at 6m is evident also. The general decrease in concentrations between the three sampling times, and the increase in concentrations at the top of the profile during the dry season, are evident.

Ammonia - (See figure 9.2 (g)) Patterns similar to ... found in the profile of TDS are displayed.

Chloride - (See figure 9.2 (h)) The Chloride content and distribution within the profile has not changed significantly during the 2 year period. The peak concentration at the 6 m level, and the increase in concentrations near the surface at the end of the dry season are evident in this analysis also.

Although the profile was sampled only to a limited depth in 1990, The results indicate that the contaminants have not moved downwards, since there is no significant increase in salt concentrations at lower levels. This again supports the theory that lateral movement of moisture in landfills is significant.

Sodium - (See figure 9.2 (i)) The sodium content was found to have decreased considerably at the end of the dry season in 1988. Two years later it has increased considerably again, once more indicating lateral moisture movement within the landfill.

Potassium - (See figure 9.2 (j)) Potassium levels show a very similar pattern to the sodium levels as discussed above.

Sulphates - For the majority of the samples, sulphates could not be measured due to interference of the sample colour with testing methods.

2.2 Linbro Park North Auger Hole

Although this auger hole was not re-sampled in 1990, except to a depth of 1m, it is discussed for comparison. The results of the analyses are shown in figures 9.3 (a) to (j).

The sampling in 1988 displays very similar trends to the South Auger hole, including the peak concentrations at the 6m level. The fact that peak concentrations of contaminants occur in both holes at similar levels, indicates that contaminants may have been transported to this level during a wet spell. It indicates that the peak is not merely due to the presence of a cell of refuse which contained high concentrations of salts when deposited.

The increased concentration of salts near the top of the profile at the end of the dry season is evident in this auger hole also.

The pH of this hole is higher than the pH of the South hole, and the COD is correspondingly lower. This indicates greater methanogenic activity in the North hole. The moisture contents within the holes are, however much the same, suggesting that although the profile is to be too dry to produce leachate, moisture conditions are not preventing methanogenic activity.

The data gathered from these two auger holes, and the monitoring boreholes, presents very strong evidence that the landfill is not producing leachate. It also presents evidence that moisture is drawn up from considerable depths, under evaporative gradients. It suggests that lateral movement of moisture within landfills is significant, and that the assumption of one-dimensional flow in calculating water balances could lead to erroneous results.

Lateral flow may arise as a result of compaction of the refuse in sloping layers. The compaction would reduce refuse permeability in the vertical direction, but not to the same extent laterally. The intermediate cover layers and cell walls, as well as layers of plastic may serve as aquicludes, while the refuse layers behave as aquifers, channelling water in the direction of the slope of the original working face of the cells.

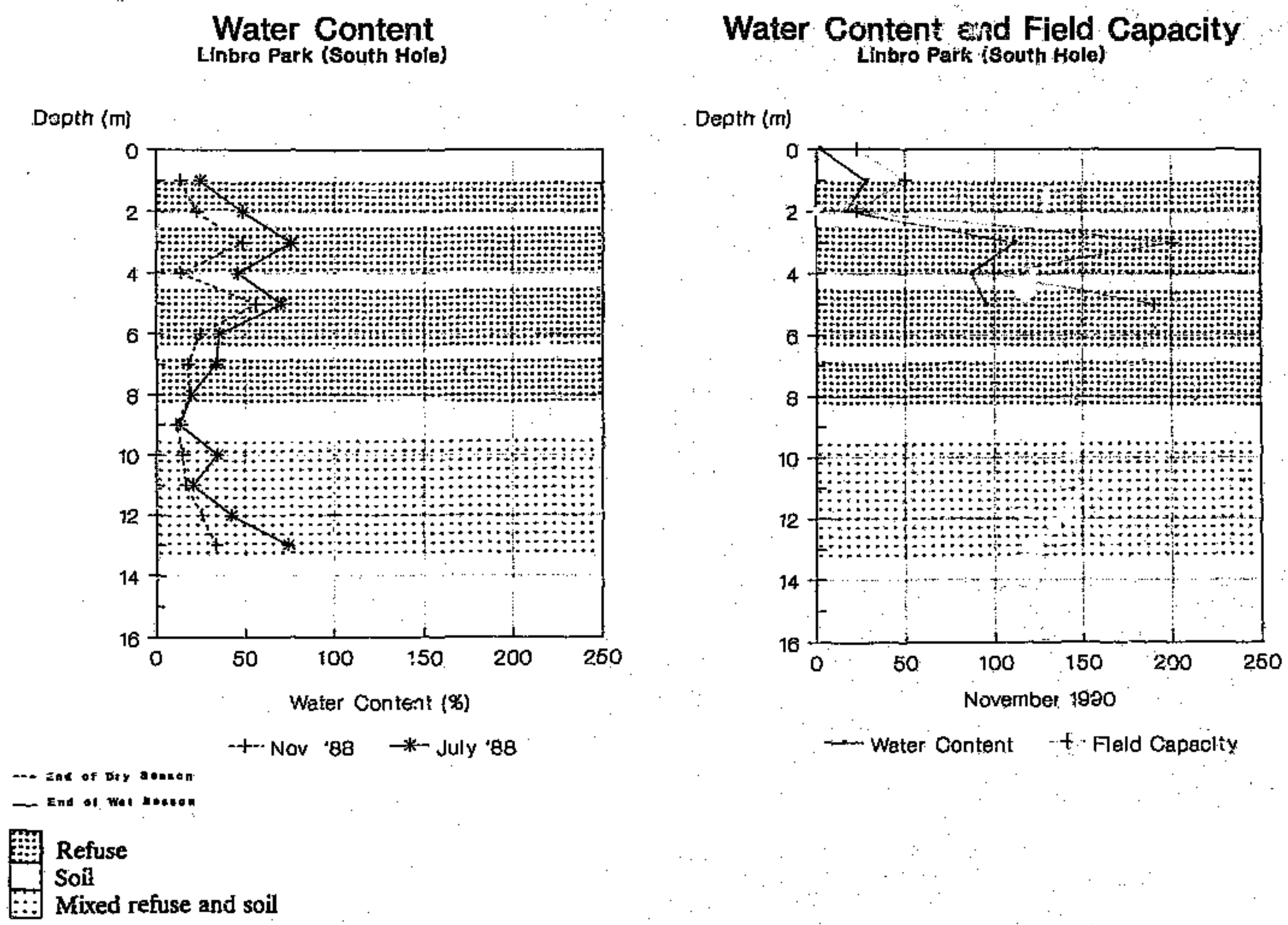


Figure 9.2 (a)
Linbro Park South Auger Hole
Water Content and Field Capacity

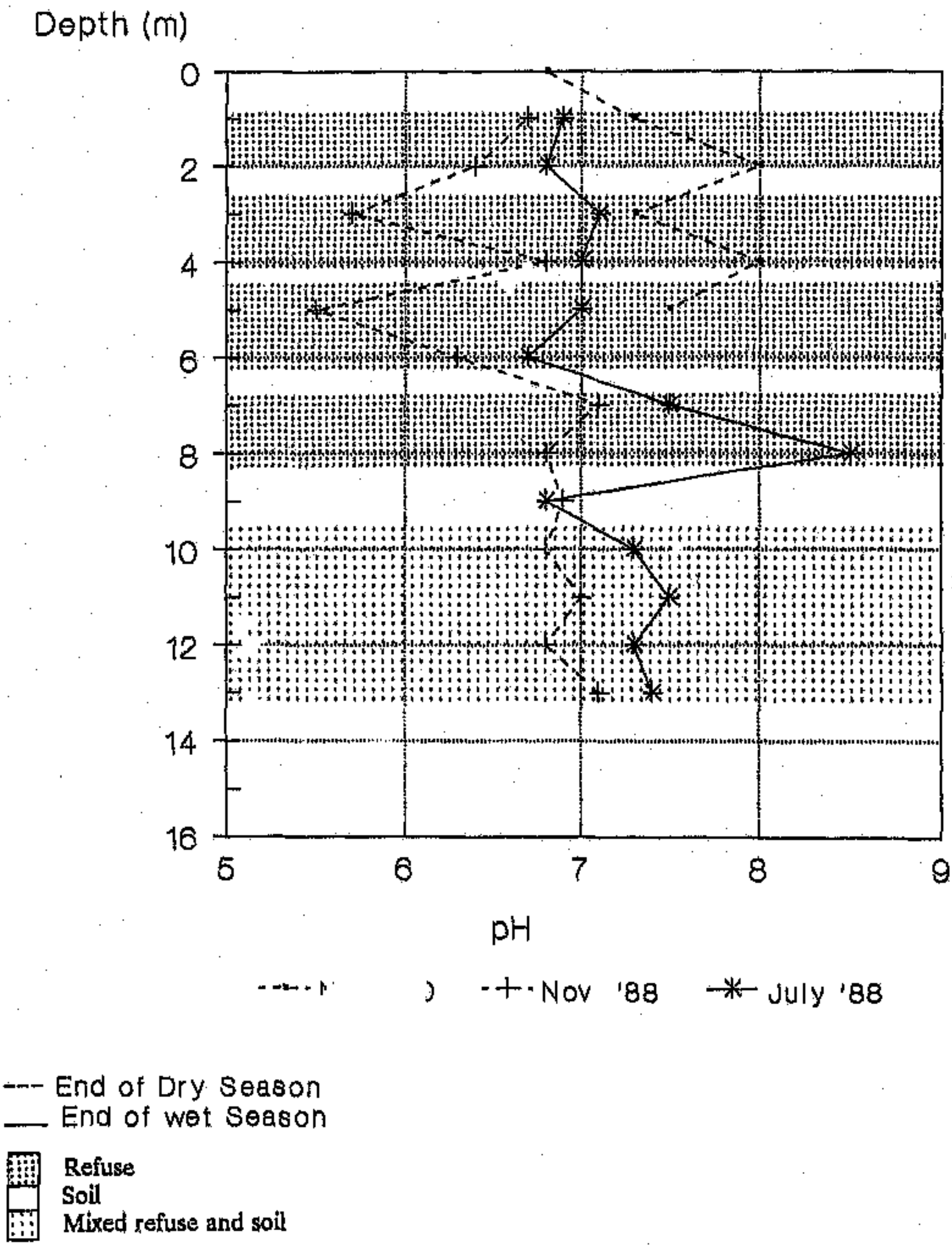
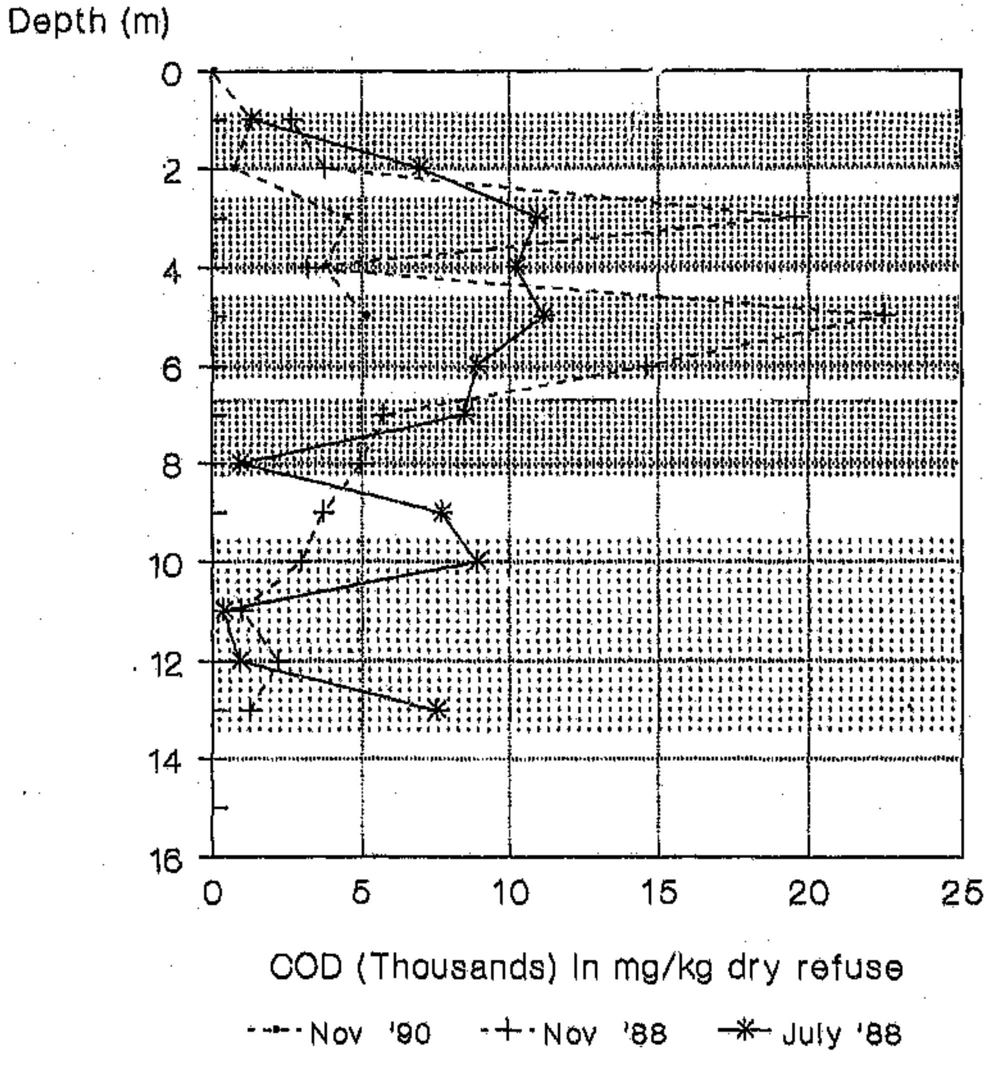


Figure 9.2 (b)
Linbro Park South Auger Hole
pH



--- End of Dry Season
___ End of Wet Season

Refuse
Soil
Mixed refuse and soil

Figure 9.2 (c)
Linbro Park South Auger Hole
Chemical Oxygen Demand

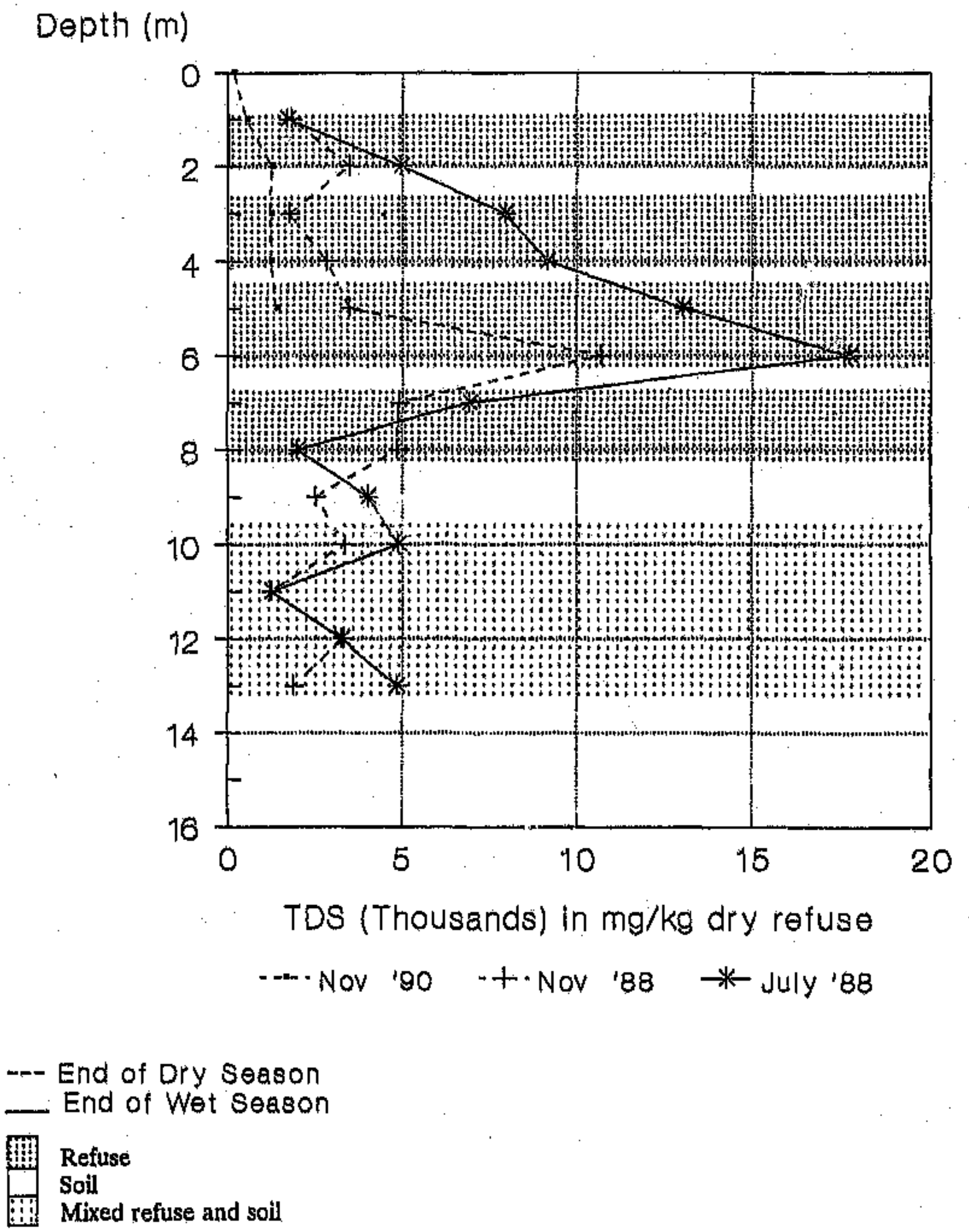


Figure 9.2 (d)
Linbro Park South Auger Hole
Total Dissolved Solids

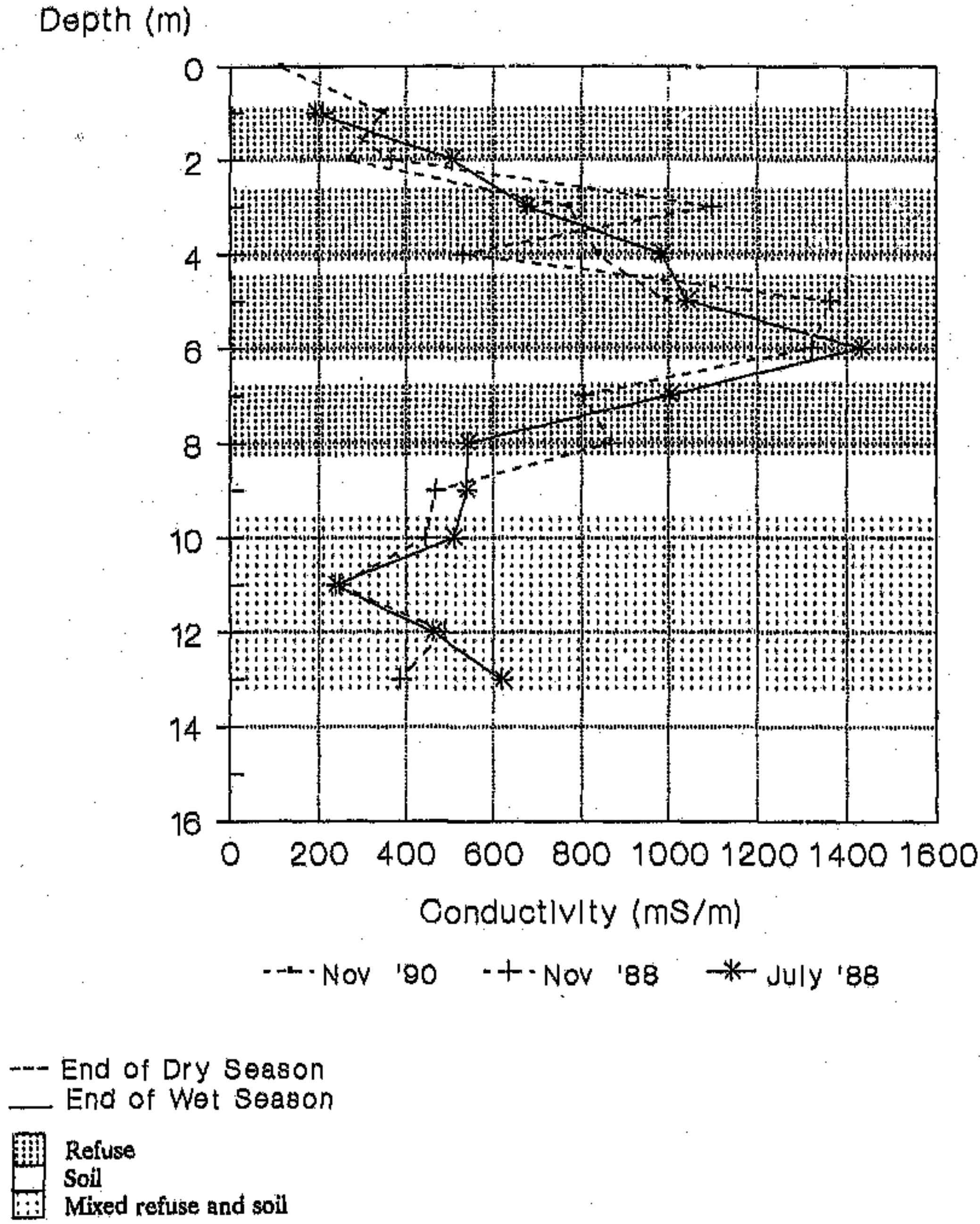


Figure 9.2 (e)
Linbro Park South Auger Hole
Conductivity

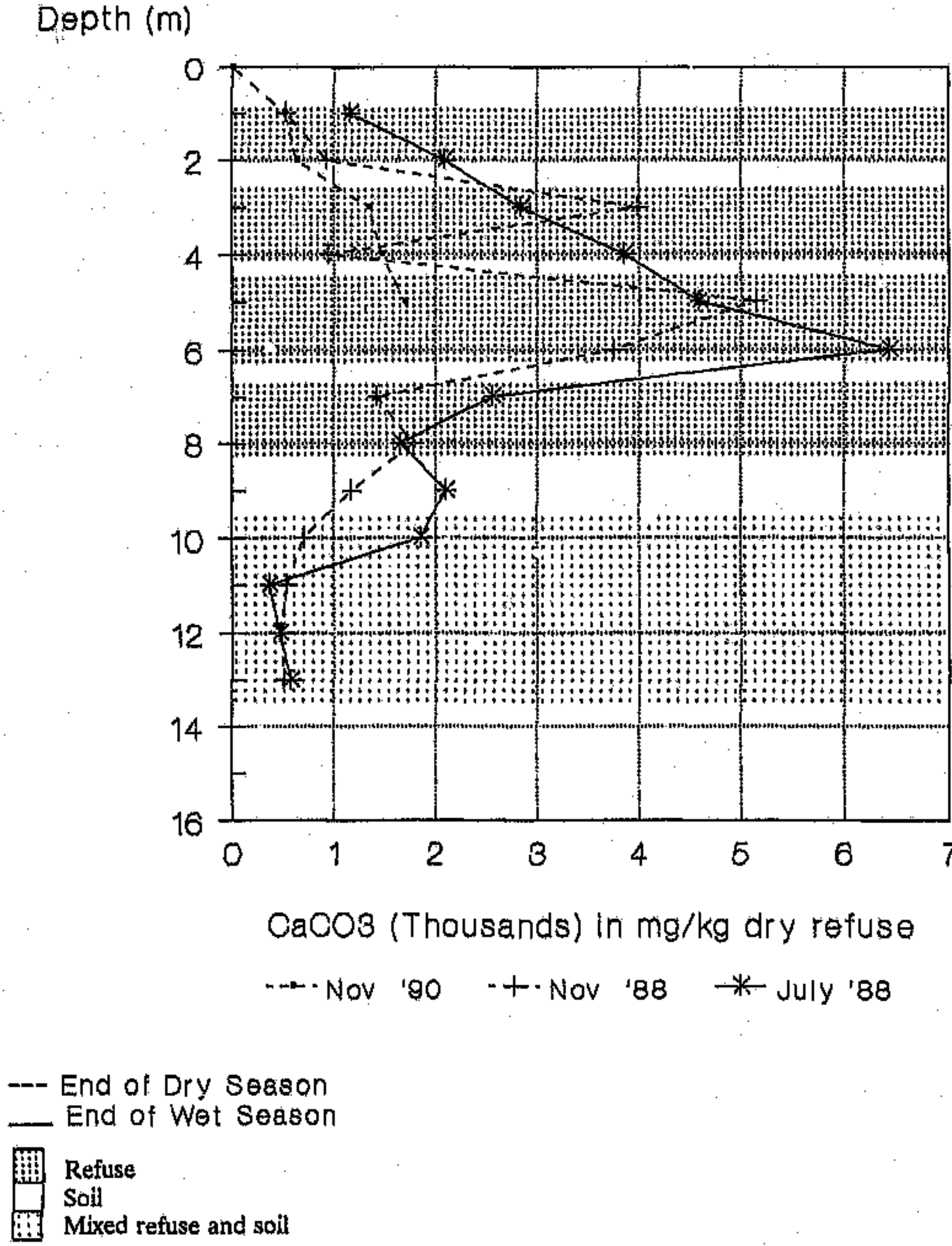


Figure 9.2 (f)
Linbro Park South Auger Hole
Alkalinity

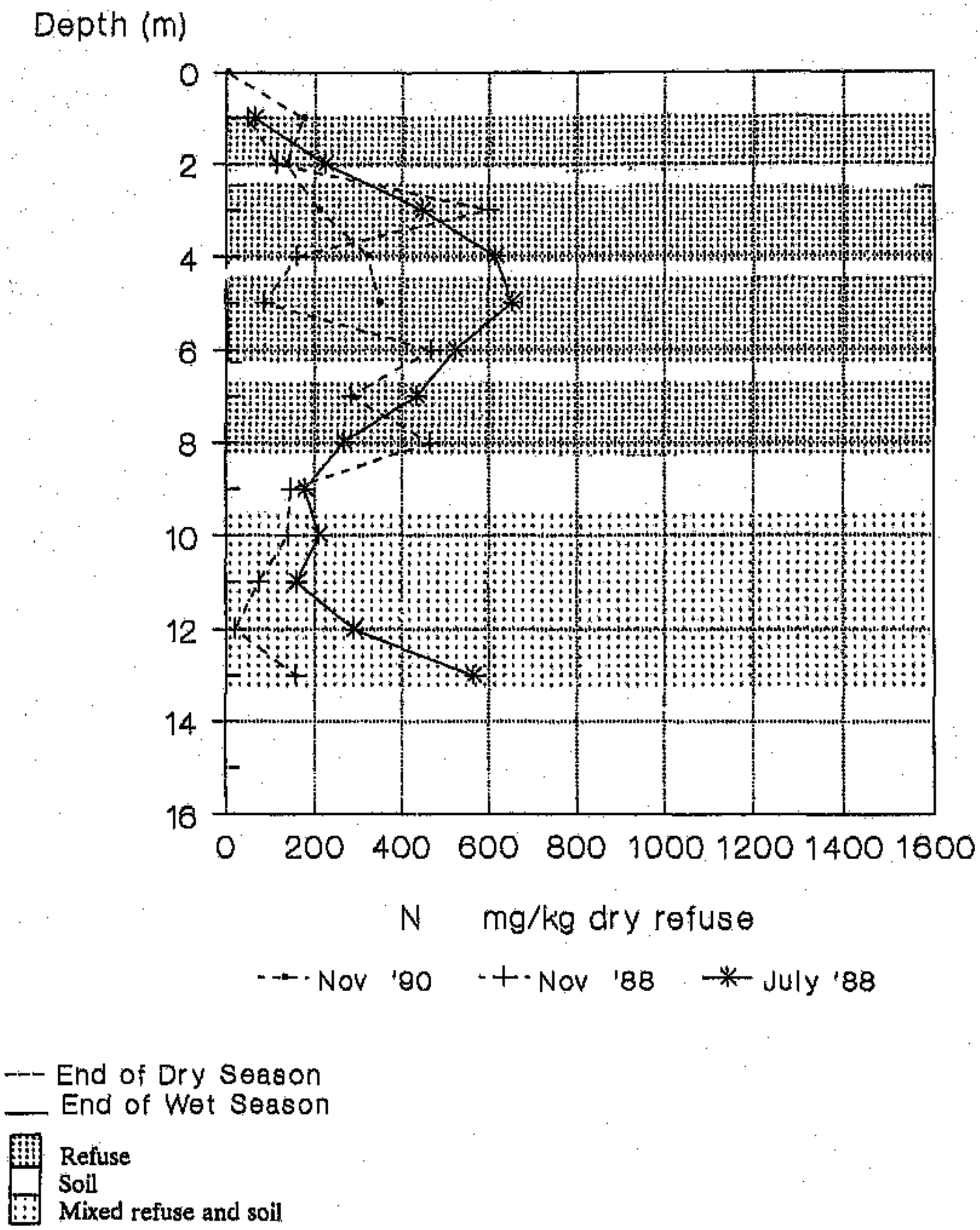


Figure 9.2 (g)
Linbro Park South Auger Hole
Ammonia (as N)

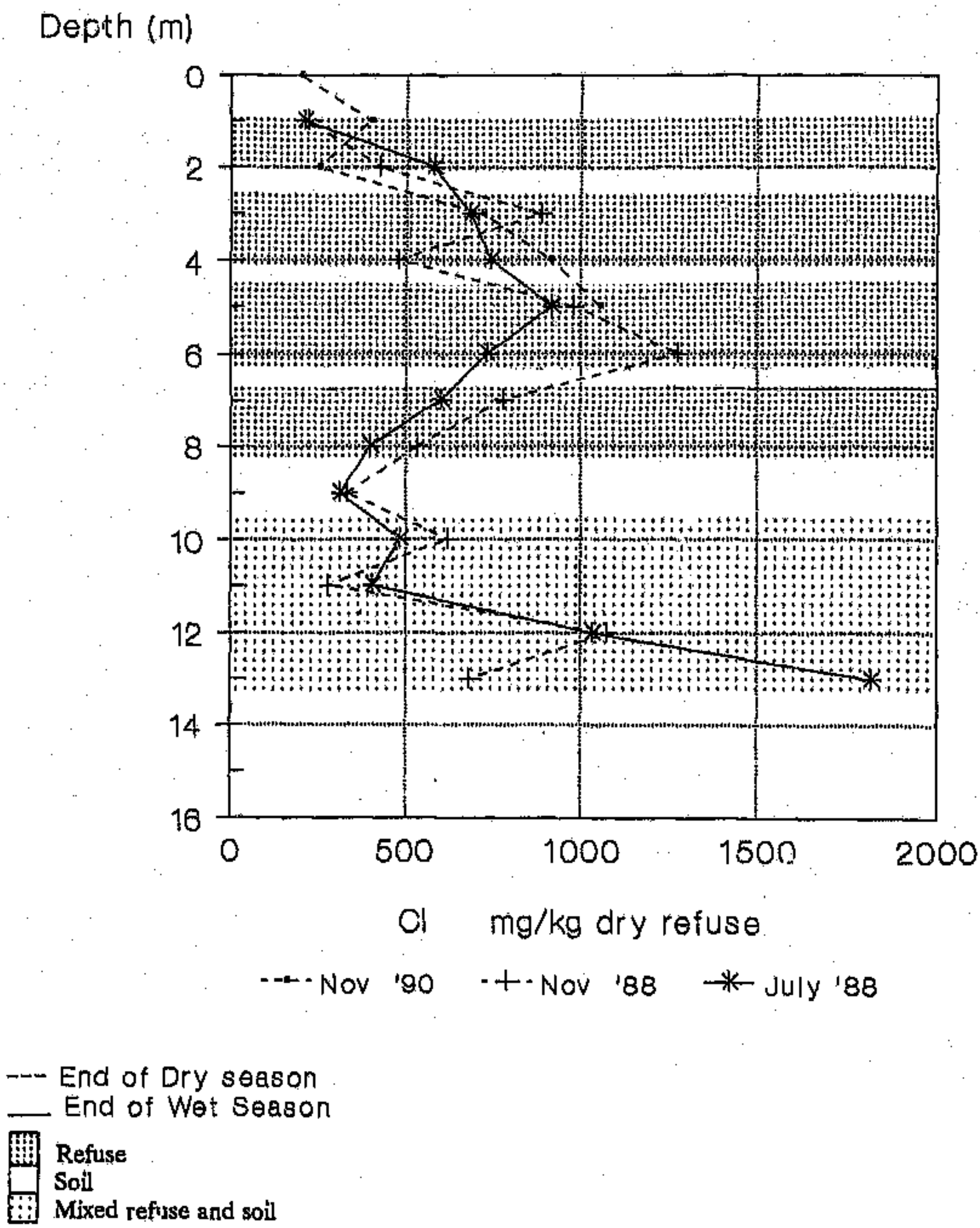


Figure 9.2 (h)
Linbro Park South Auger Hole
Chloride (as Cl)

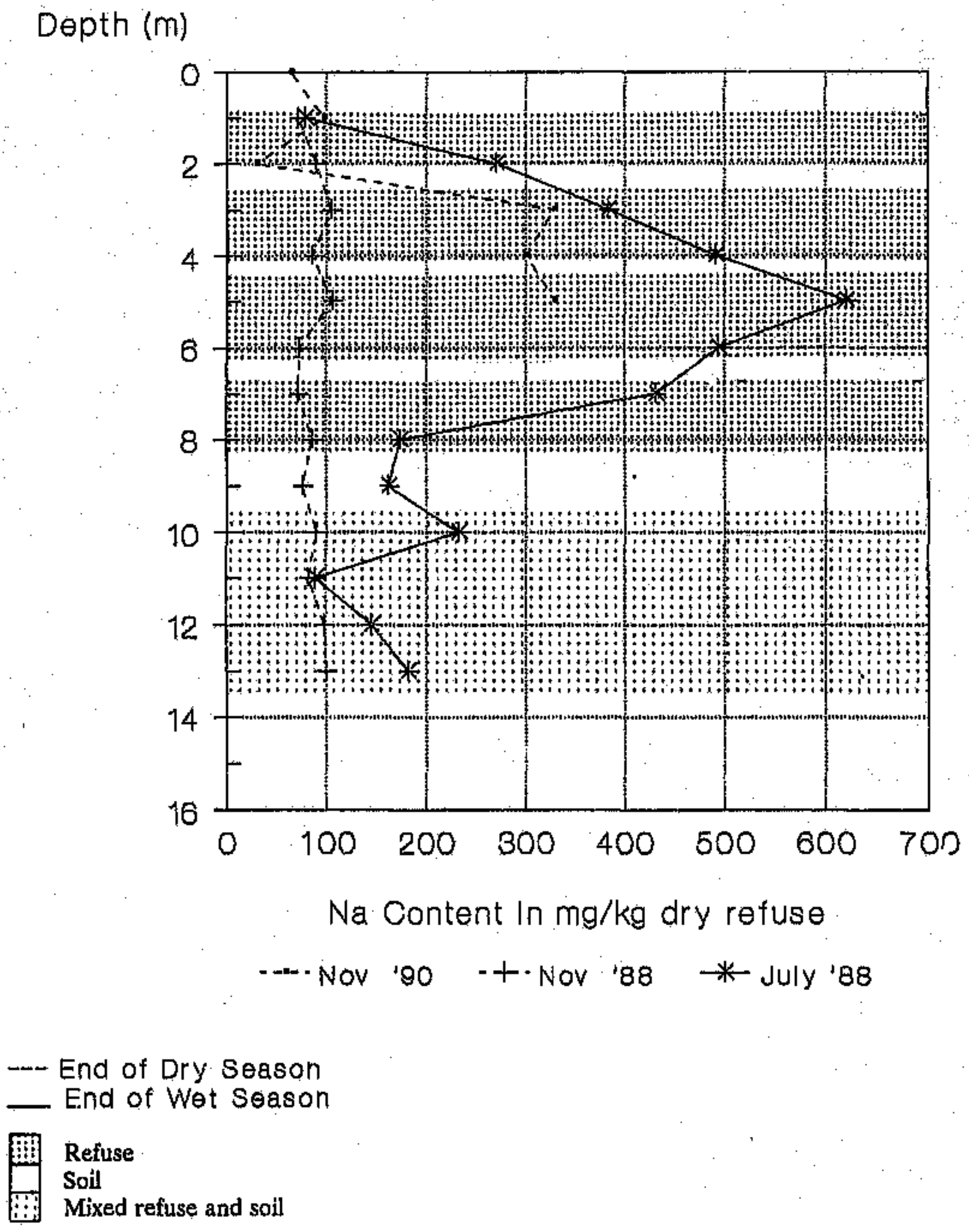


Figure 9.2 (i)
Linbro Park South Auger Hole
Sodium (as Na)

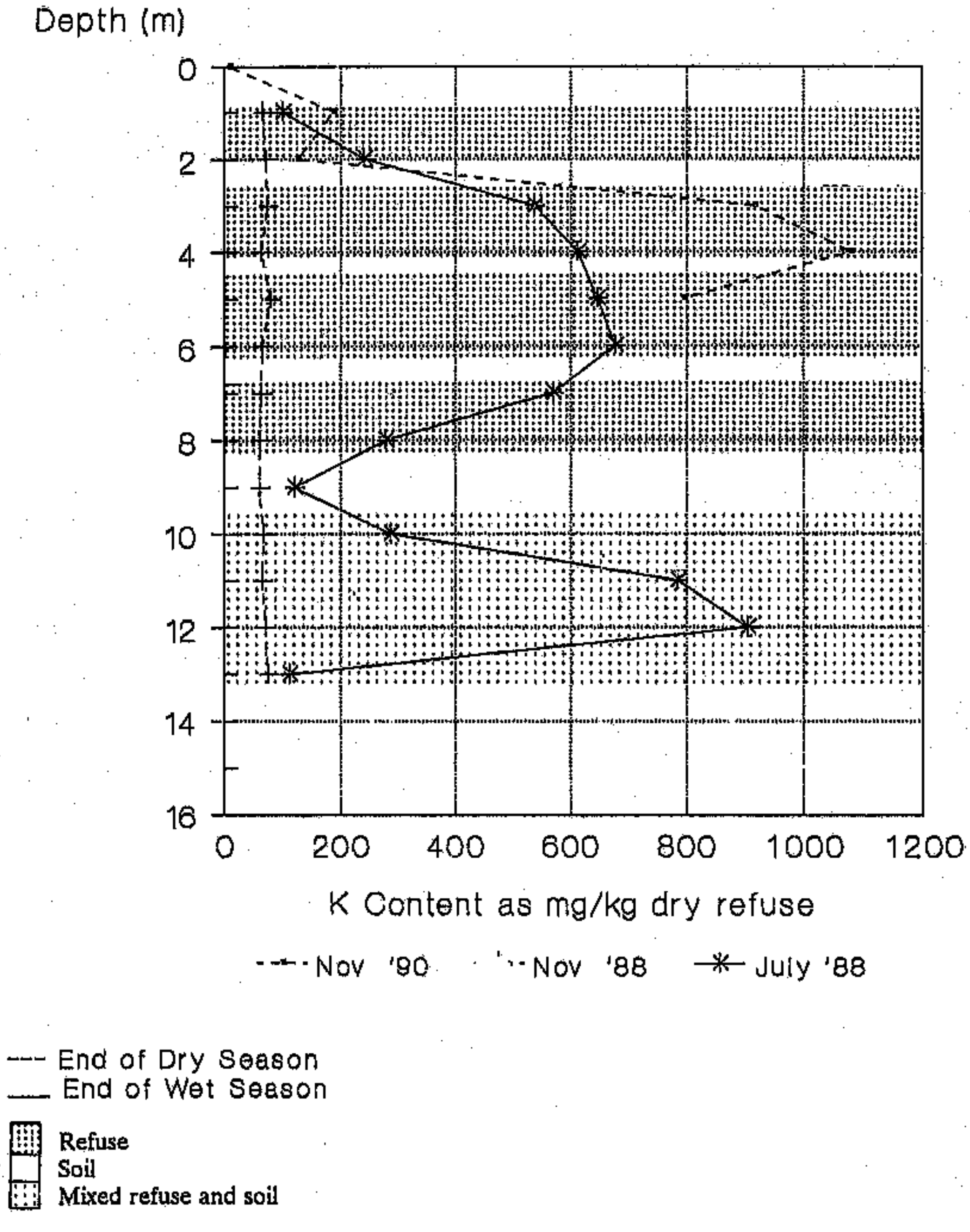


Figure 9.2 (j)
Linbro Park South Auger Hole
Potassium (as K)

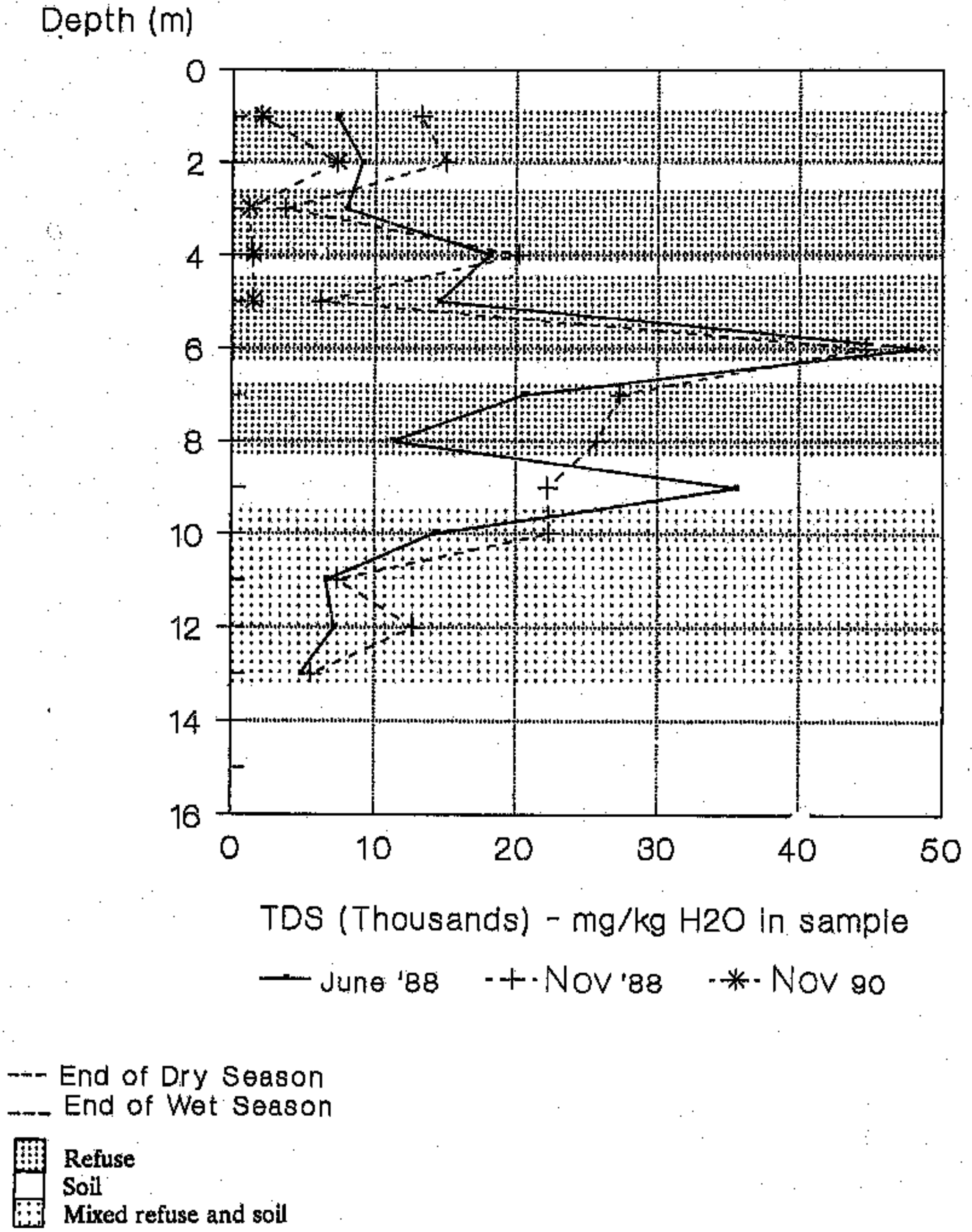


Figure 9.2 (k)
Linbro Park South Auger Hole
Total Dissolved Solids (Expressed as mg/kg of water contained within refuse.)

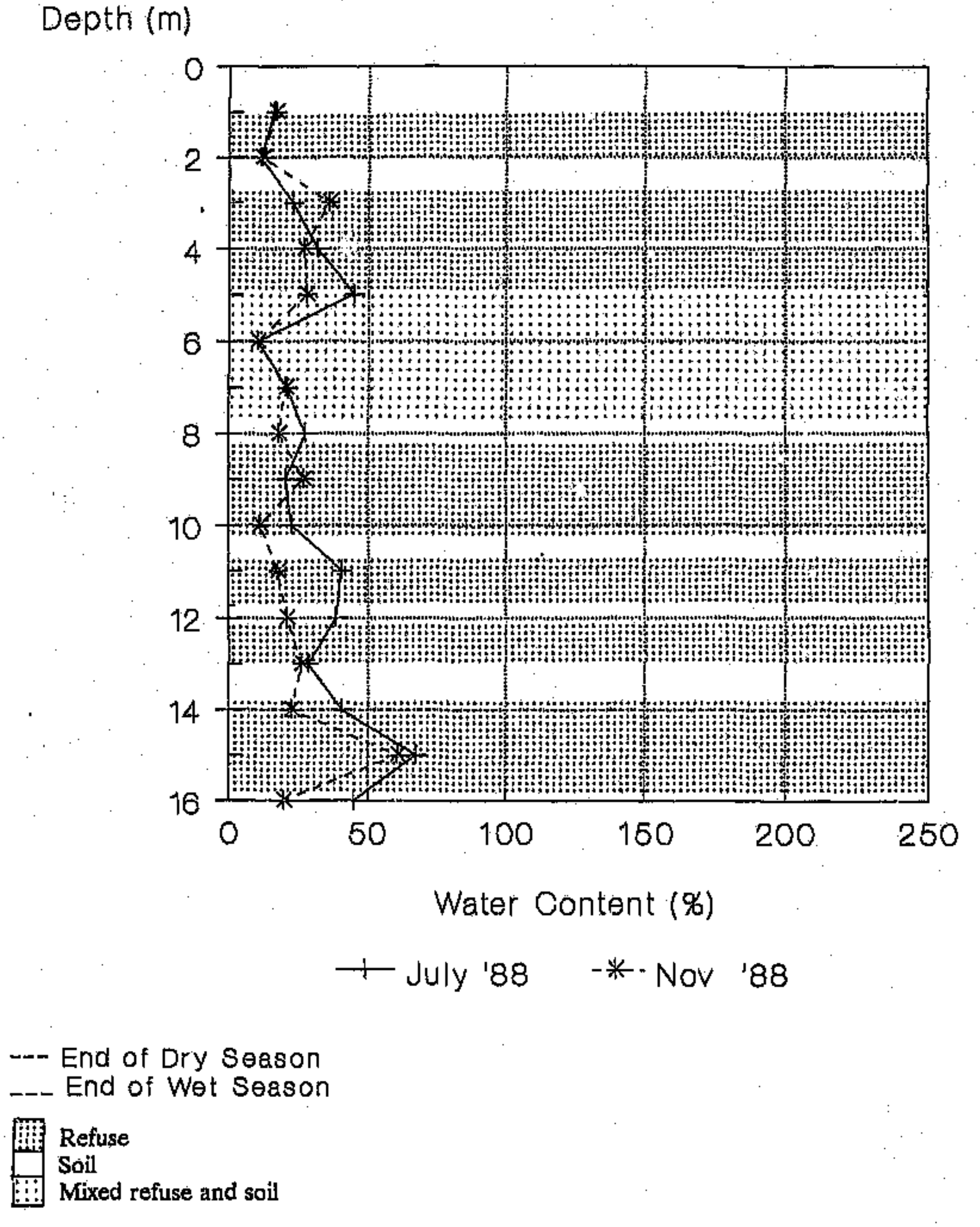


Figure 9.3 (a)
Linbro Park North Auger Hole
Water content and Field Capacity

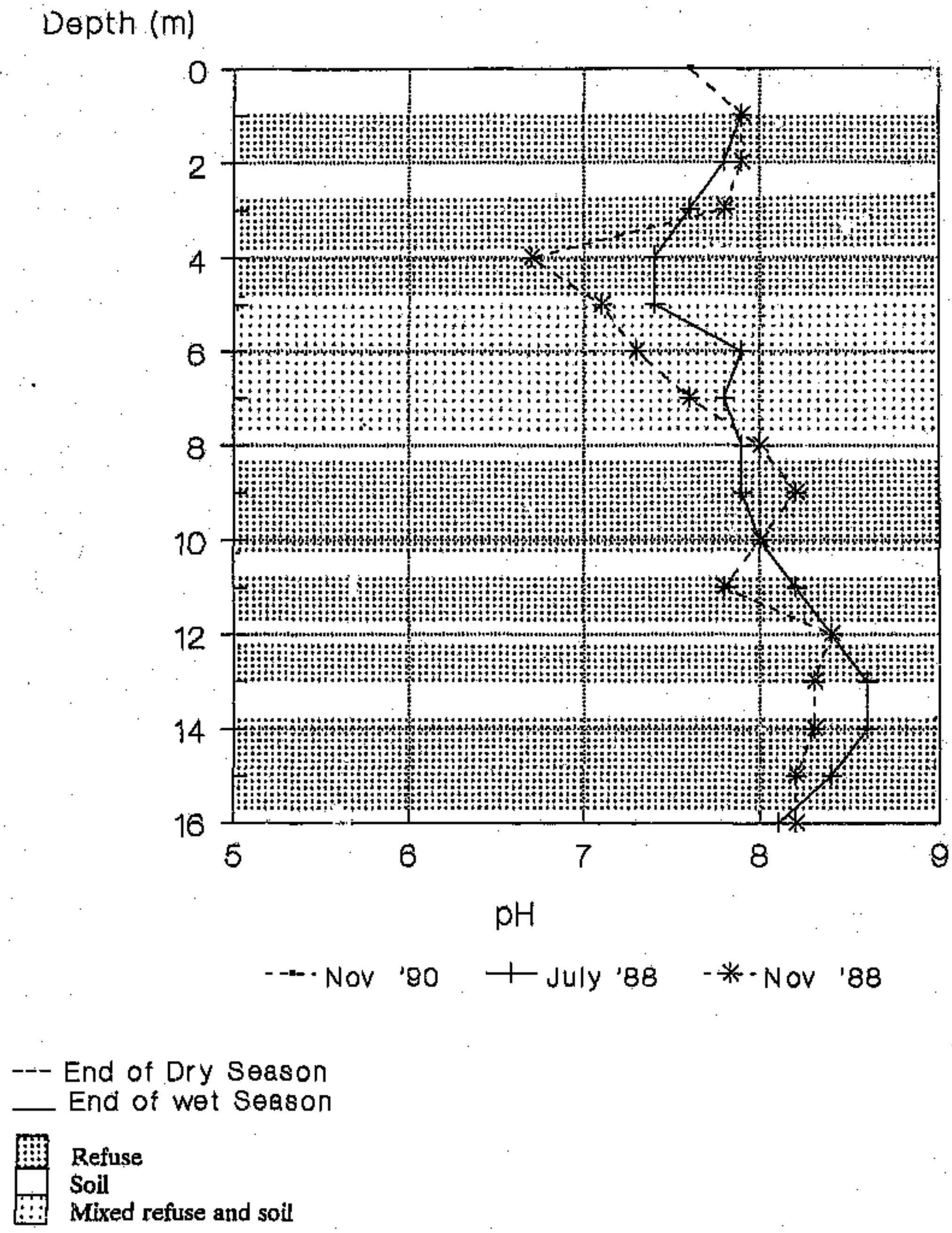


Figure 9.3 (b)
Linbro Park North Auger Hole
pH

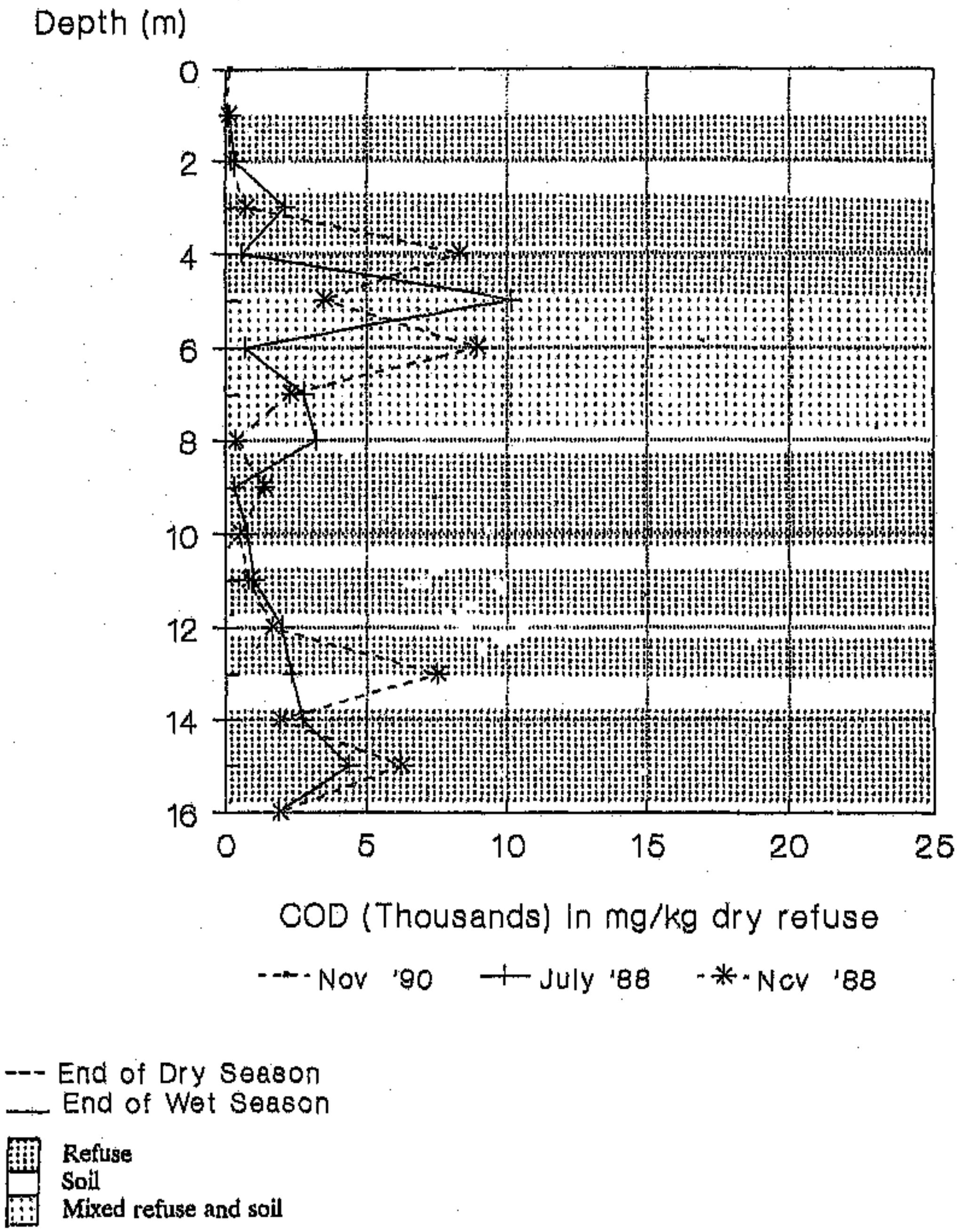


Figure 9.3 (c)
Linbro Park North Auger Hole
Chemical Oxygen Demand

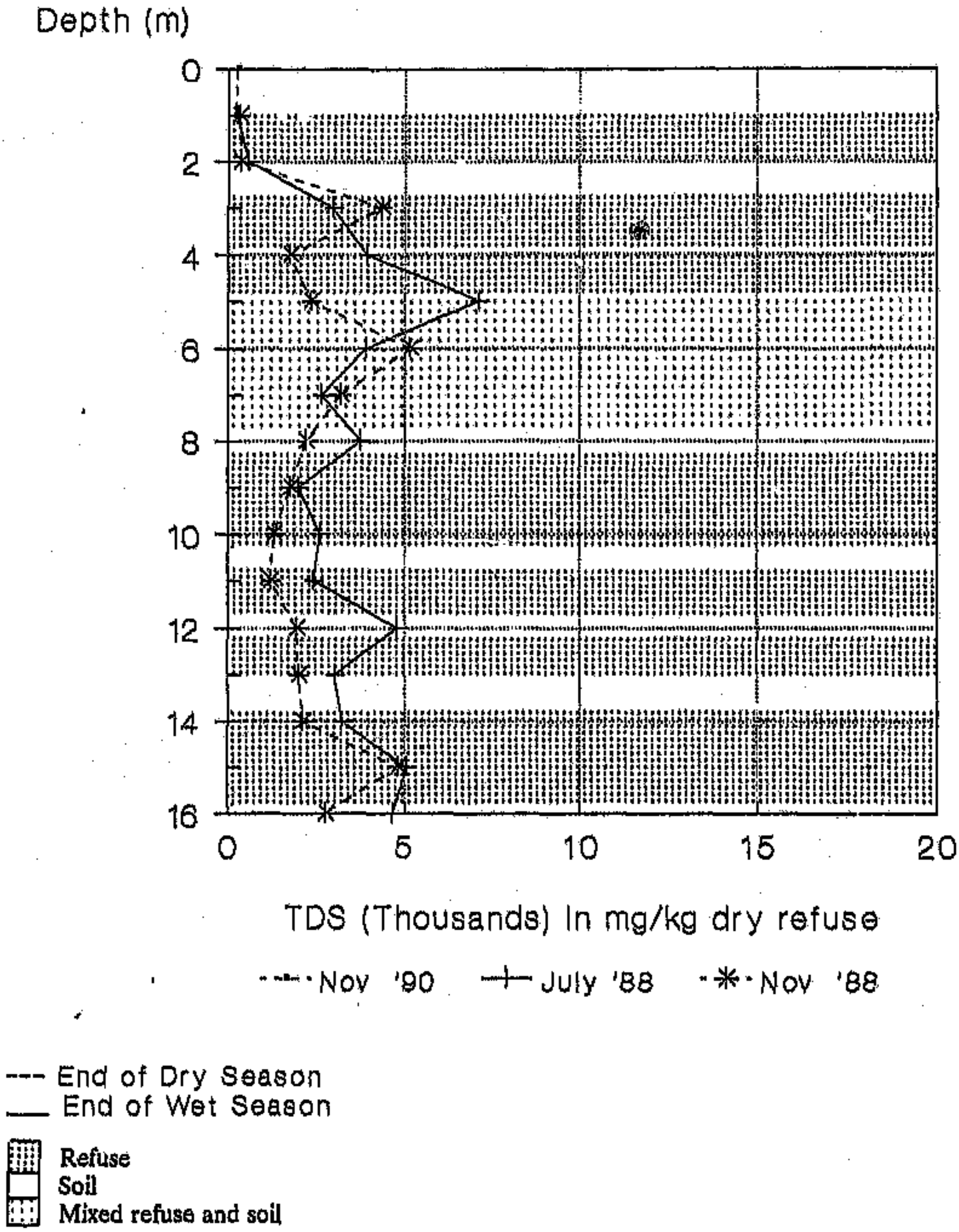


Figure 9.3 (d)
Linbro Park North Auger Hole
Total Dissolved Solids

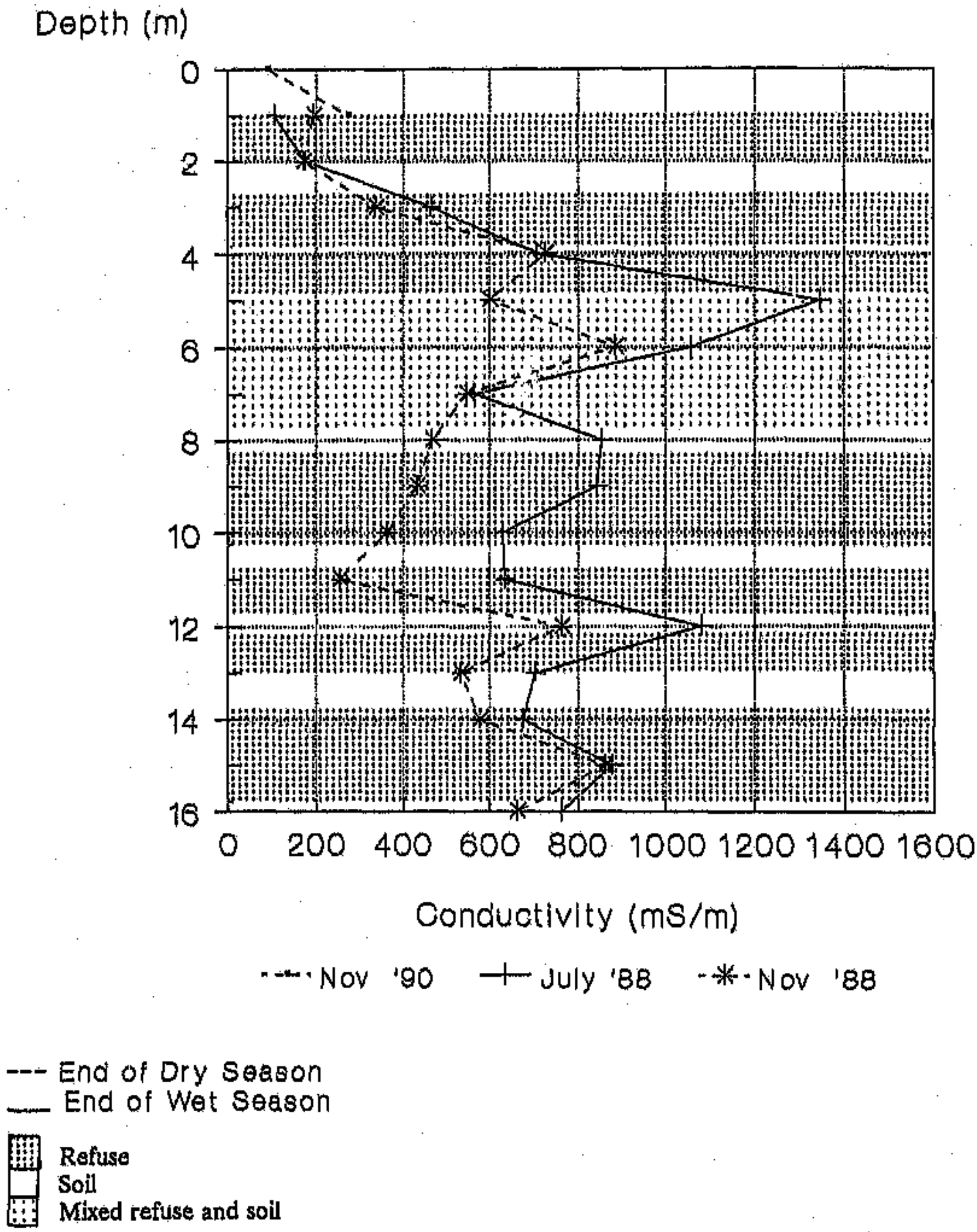


Figure 9.3 (e)
Linbro Park North Auger Hole
Conductivity

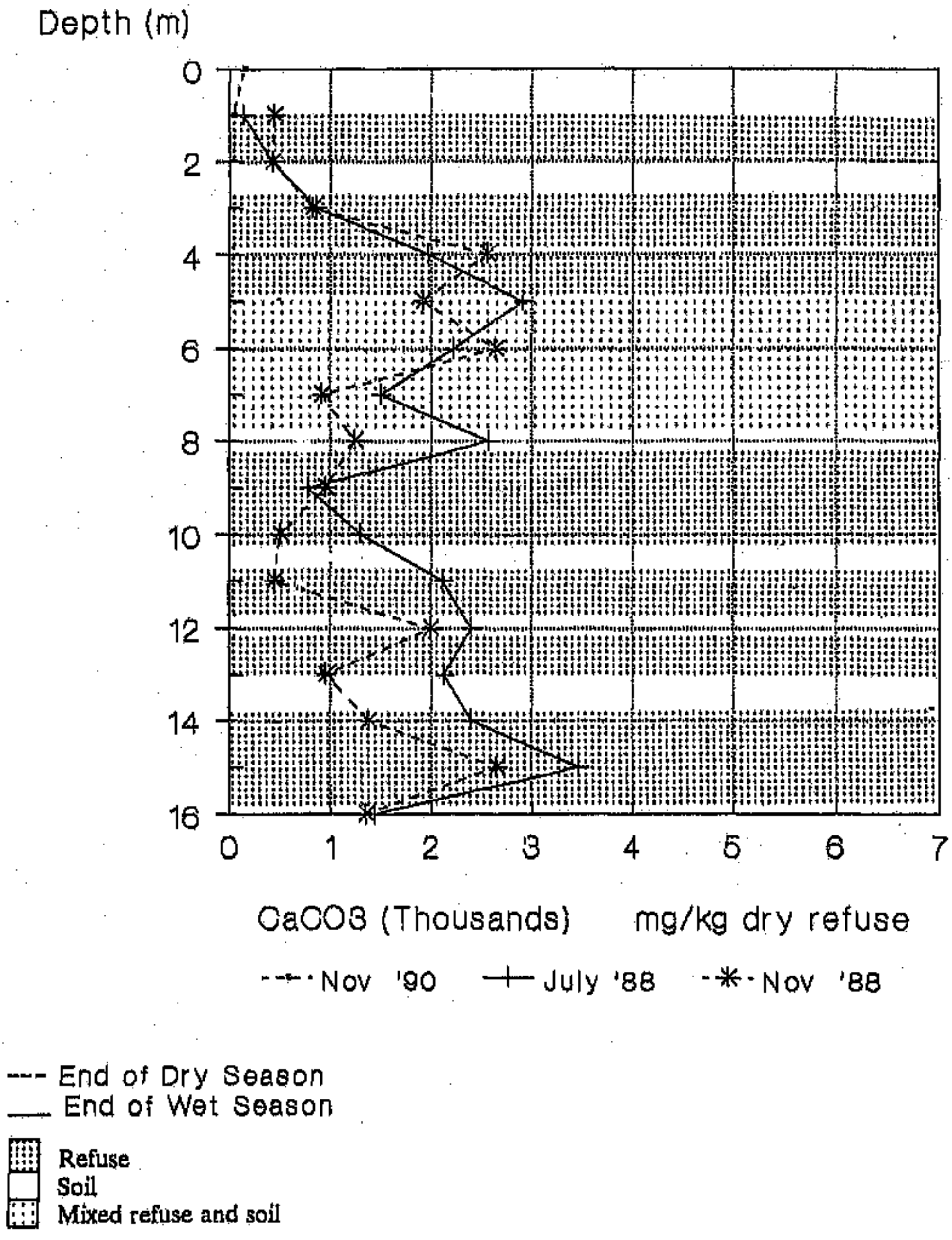
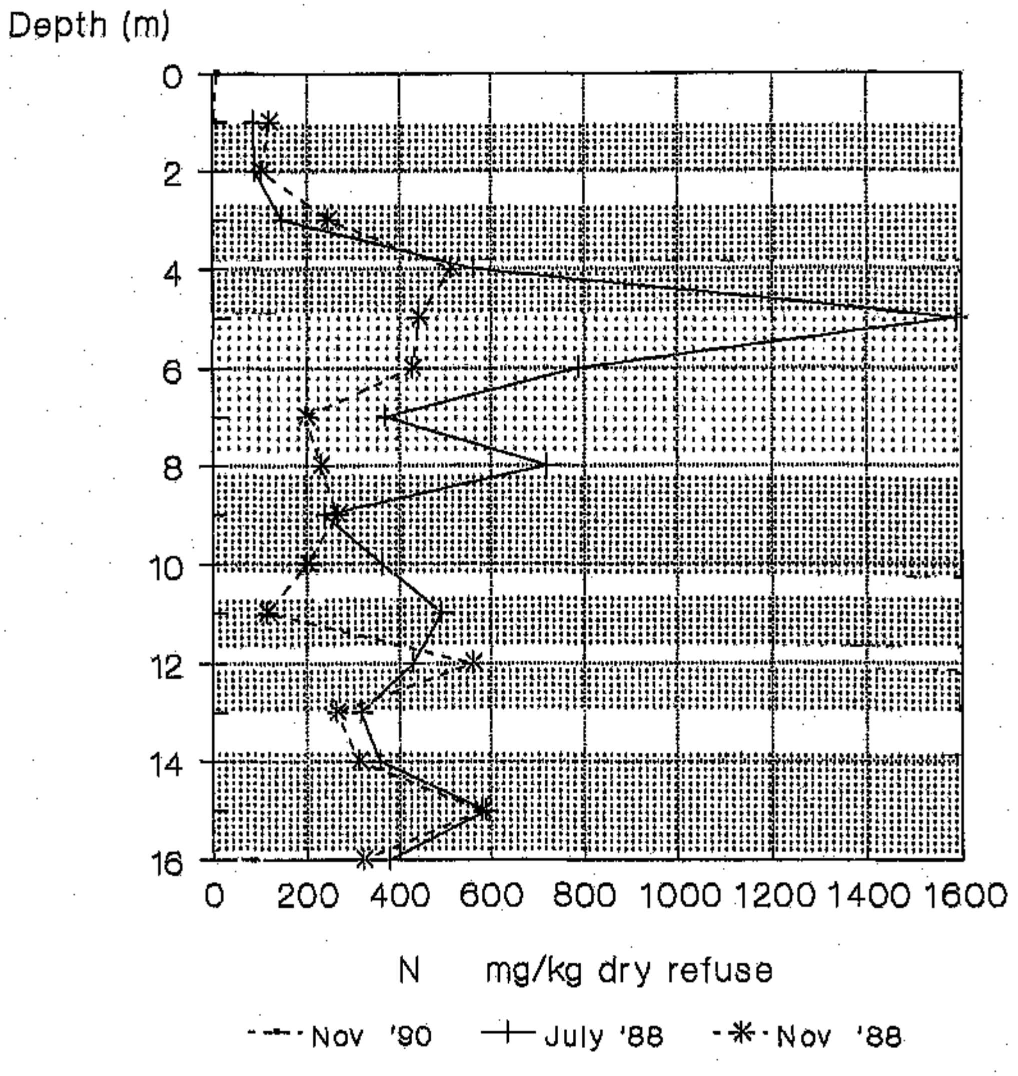


Figure 9.3 (f)
Linbro Park North Auger Hole
Alkalinity (as $CaCO_3$)



--- End of Dry Season
___ End of Wet Season

Refuse
Soil
Mixed refuse and soil

Figure 9.3 (g)
Linbro Park North Auger Hole
Ammonia (as N)

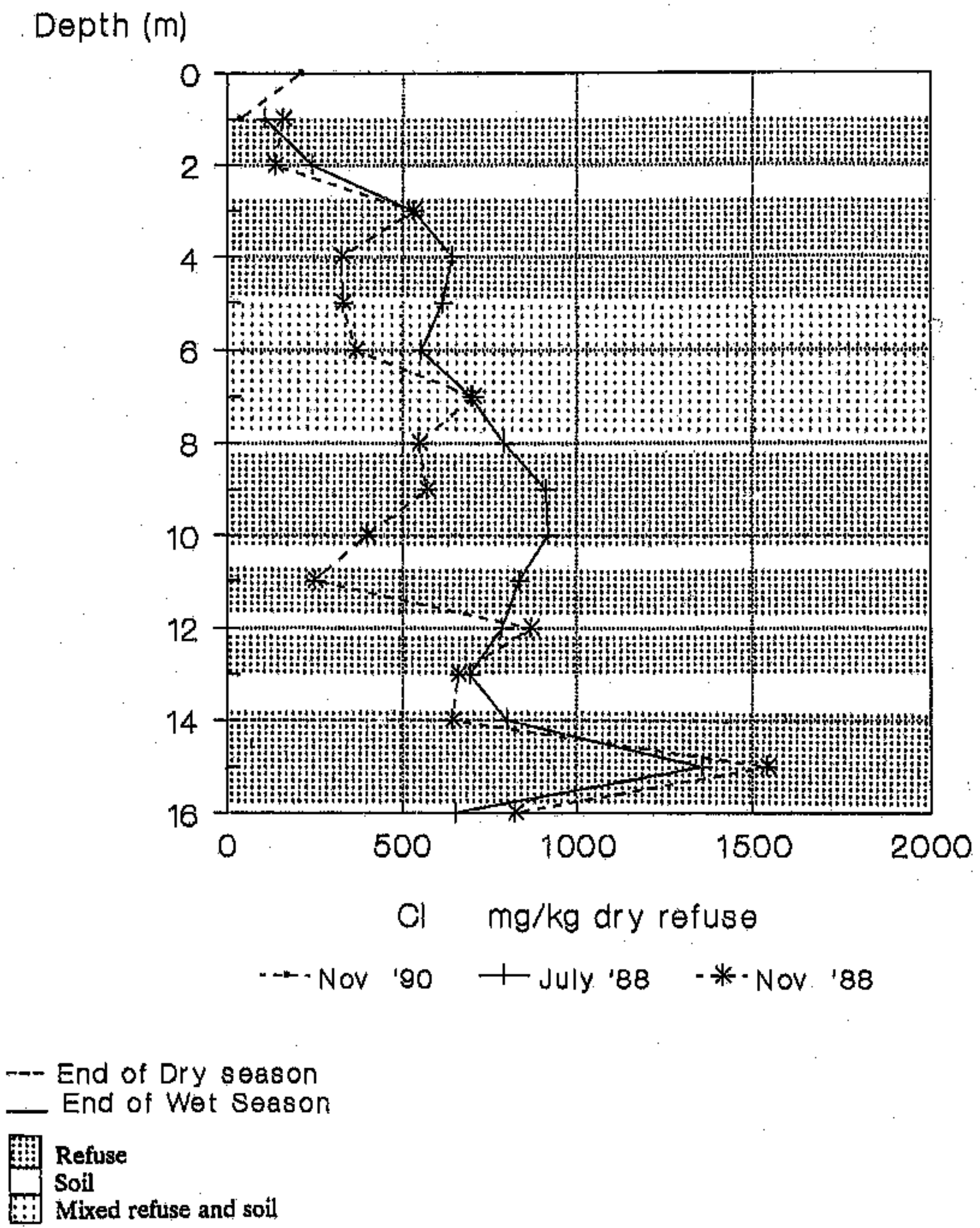


Figure 9.3 (h)
Linbro Park North Auger Hole
Chloride (as Cl)

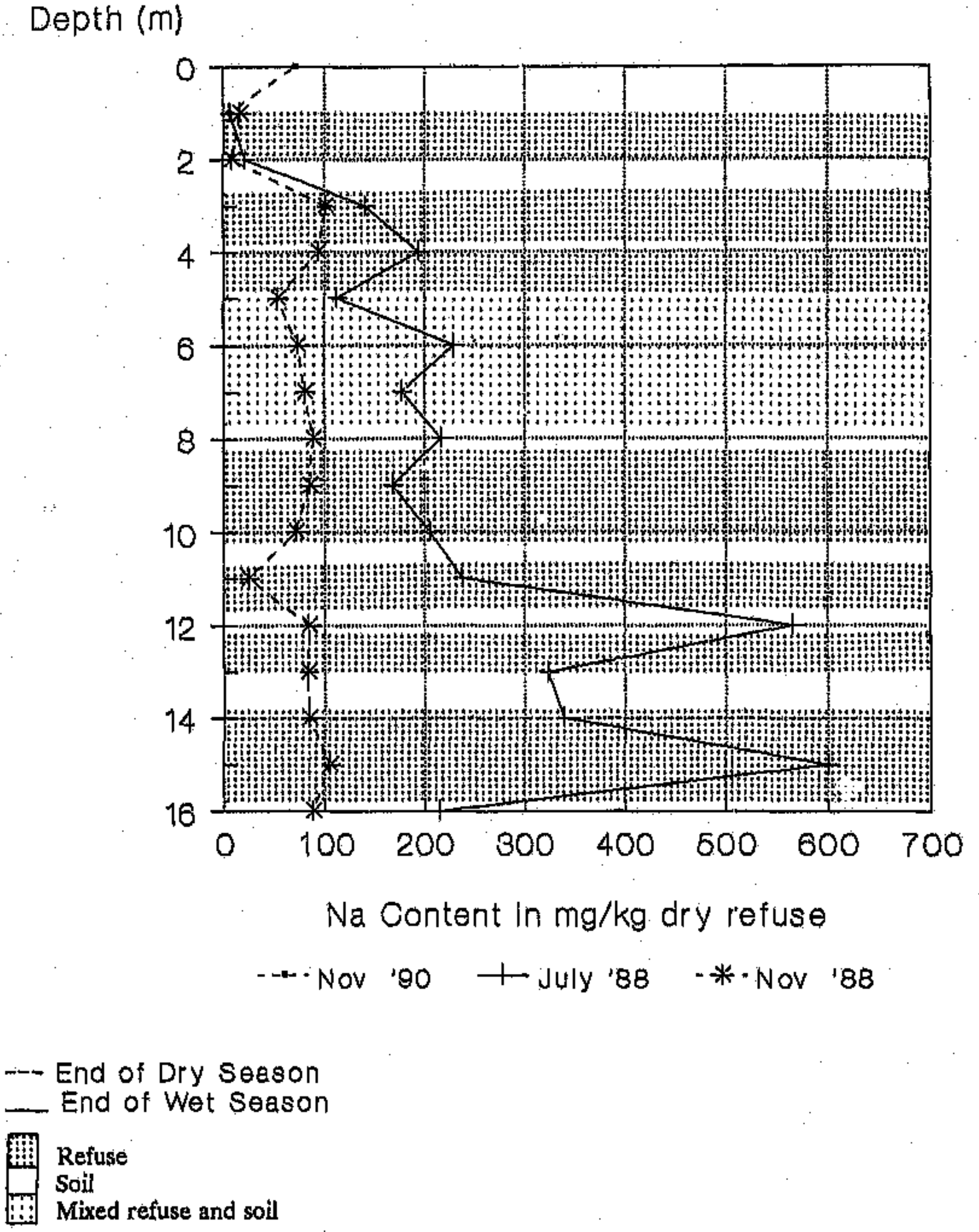


Figure 9.3 (l)
Linbro Park North Auger Hole
Sodium (as Na)

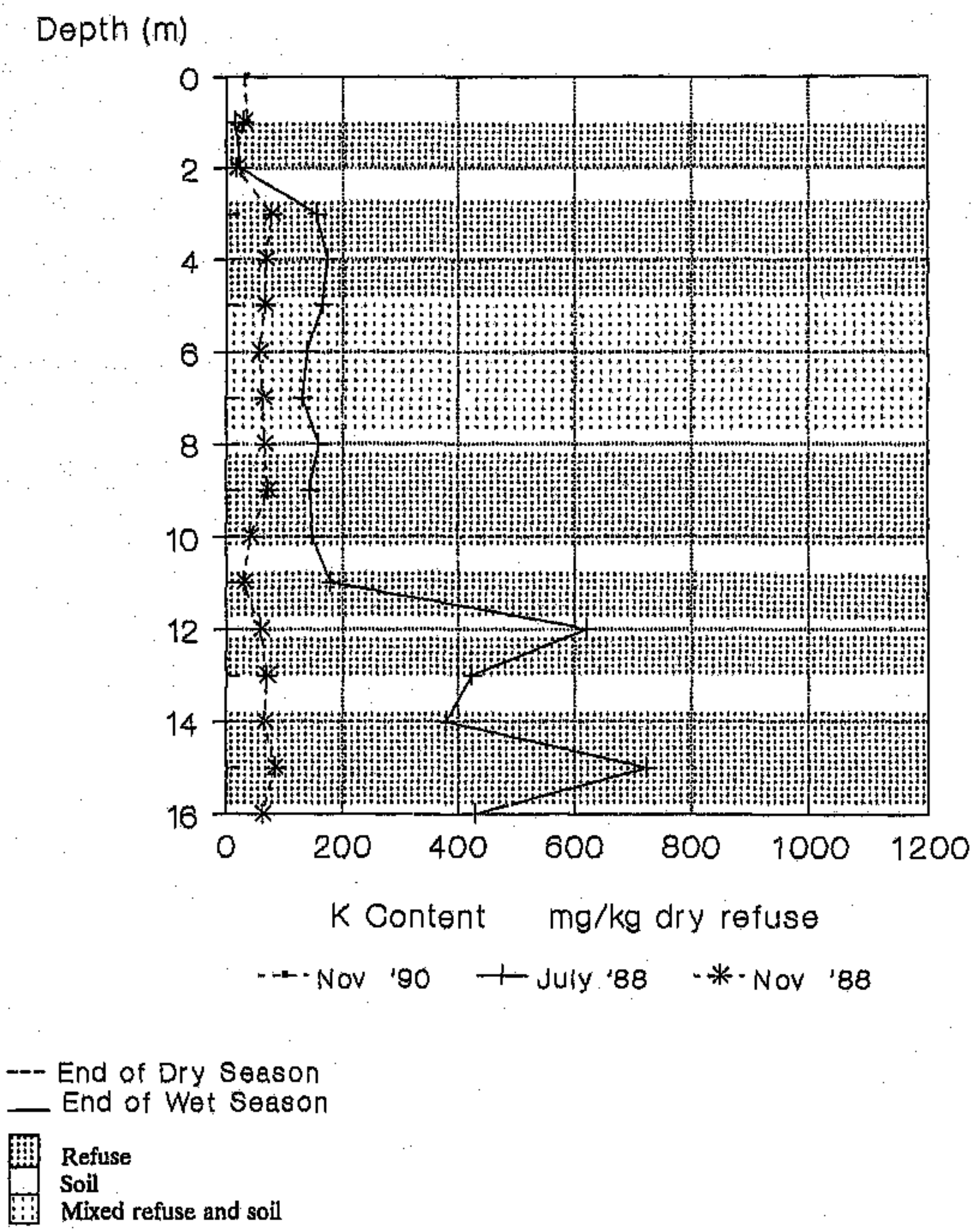


Figure 9.3 (j)
Linbro Park North Auger Hole
Potassium (as K)

CHAPTER 10

INFILTROMETER TESTS

It is chiefly on the basis of natural soil surfaces that methods for estimating infiltration have been developed. Landfill surfaces are significantly different to natural soil surfaces. Landfill covers crack extensively as a result of uneven settlement, the vegetation may be poorer, and shallow rooted, and often the upper layers of the cover material consist not of top soil, but materials such as sub-soil, builders' rubble, and mine tailings. Existing methods of predicting infiltration may therefore not be suitable for application to landfills.

Field tests to evaluate magnitudes of infiltration into the cover of the test section of the Linbro Park landfill were carried out. The cover of the test section comprises sub-soil, and has cracked extensively under settlement. Two sets of tests were performed. The first series of tests utilised ring infiltrometers, while the second series utilised a sprinkler infiltrometer. The results obtained are compared to the results of existing methods of predicting runoff.

1 RING INFILTROMETER TESTS

In order to obtain some idea of the upper limits of the infiltration capacity of the landfill profile, a series of ring infiltrometer tests was performed. The tests were carried out using distilled water as well as tap water. This was done so that the effects of the chemistry of the infiltrating water, on infiltration rates could be assessed. This information was used in the design of the sprinkler infiltrometer (which is described in section 2 of this chapter.)

1.1 Water and Soil Chemistry, and Infiltration

A large volume of water is required for sprinkler infiltrometer tests, especially if an area large enough to be representative of the surface of a landfill, is to be used. It has been mentioned in Chapter 7 that the chemistry of the water used to simulate rainfall may be important in infiltration tests. Obtaining enough distilled water (which is chemically most representative of rain water), to perform the tests is difficult and expensive. The only water which is available on the test site is Rand Water Board (RWB) Water. If RWB water was to be used, the effects of the differences in chemistry between this and distilled water needed to be known.

1.1.1 Rain Water Quality vs RWB Water Quality

The results of chemical analyses of rain water in the Johannesburg area, and of RWB water are shown in figure 10.1. The figures given for rain water are based on 20 analyses carried out by Johannesburg City Council, on rain water from the suburb of Montgomery Park, in North West Johannesburg.

It would have been preferable to have rain water quality data for the site in question, but this was not possible due to time constraints. The test site is located within a few kilometres of the township of Alexandra, and the chemical industries of Modderfontein and Chloorkop (which are point sources of air pollution.) The site for which the rain water analysis was carried out is located much further away from such point sources of pollution. Annegarn, (pers. comm. 1991,) has, however, found that air pollutants disperse so quickly on the Transvaal Highveld that the concentrations of pollutants in rain water from these two sites may be expected to differ at most by a factor of two. The figures presented here are therefore considered to be adequate for the degree of accuracy required for this study.

The analysis of the RWB water was also supplied by Johannesburg City Council, and is based on results of about 46 sets of tests. As can be seen the concentrations of all minerals is considerably higher in the RWB water. The pH of the rain is low (4.2), while the pH of the RWB water is 7.5. Most notably, the hardness of the RWB water is very much greater than that of rain water.

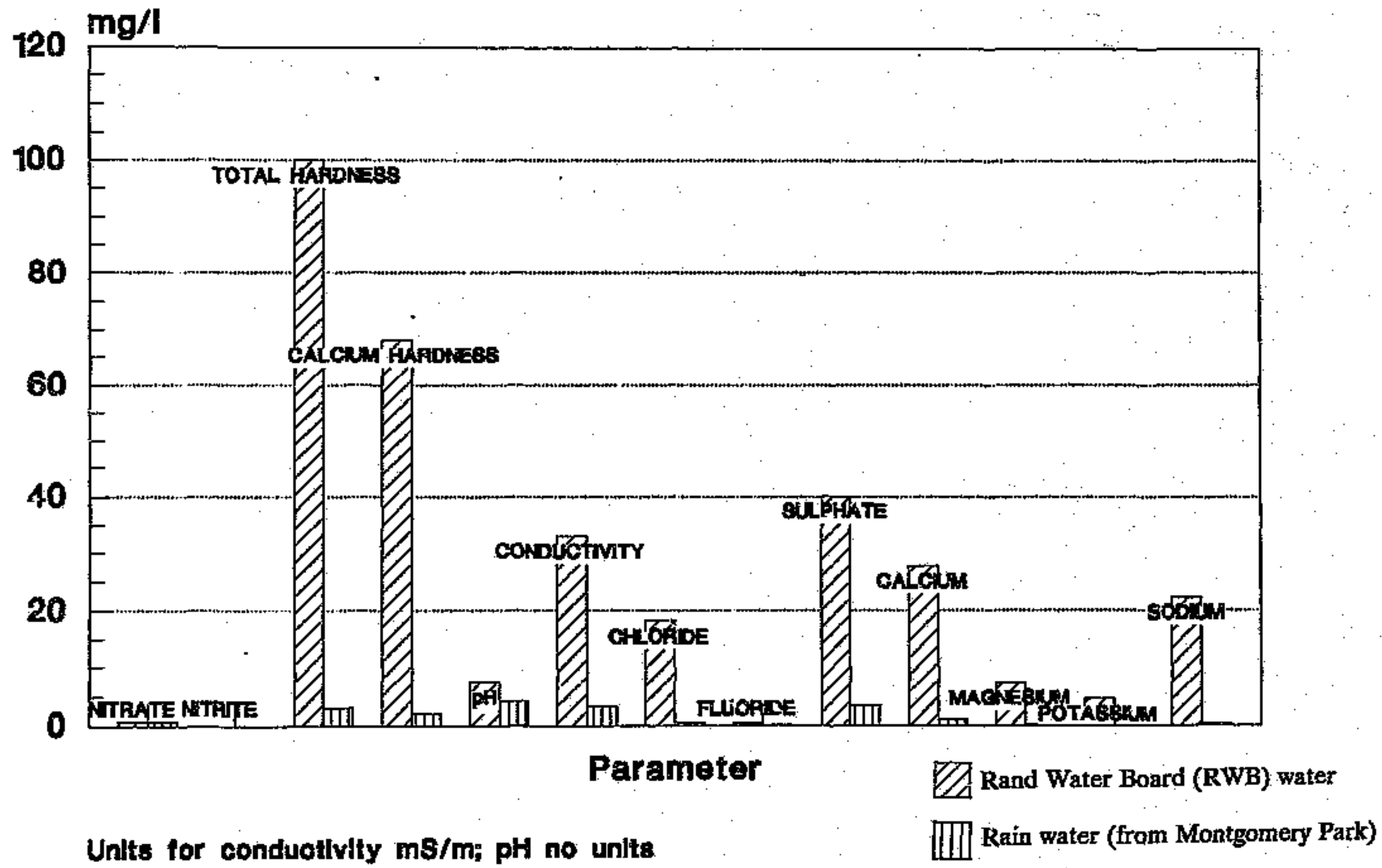


Figure 10.1
A comparison between the chemical properties of rain water in the Johannesburg area, and Rand Water Board Water

1.1.2 Soil Chemistry and Permeants

An explanation of the effects of acids and inorganic and organic compounds, on the permeability of soils is given in EPA/625/4-89/022, 1989. The document explains how Gouy-Chapman Theory relates electrolyte concentration, cation valence, and dielectric constant of the permeant to the thickness of the so-called 'diffuse double layer'* In addition to affecting the double layer, acids dissolve constituents of soil and so cause hydraulic conductivity to decrease. This effect is only important for concentrated acids.

The relationship given by the Gouy-Chapman equation is quoted below:

$$t \;\alpha\; \frac{D}{\sqrt{n_o V^2}} \tag{10.1}$$

where: t is the thickness of the double layer

D is the dielectric constant of the permeant

n_o is the electrolyte concentration

V is the cation valence

This equation predicts that the higher electrolyte concentration in RWB water would decrease the thickness of the double layer, and so increase the hydraulic conductivity of the soil.

The way in which the chemistry of the rain water affects permeability is also dependant on the chemical properties of the soil. The soil at Linbro Park has a high percentage of exchangeable sodium. (The ESP equals 17.5%, as stated in Chapter 8.) The soil has a low calcium content. (16 mg/kg, Hojem, 1988) If the soil were to be irrigated with calcium rich water one would therefore expect sodium ions to be exchanged for calcium ions (which have a higher valency,) and the hydraulic conductivity to increase.

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* Cations in water are attracted to the negatively charged surfaces of the clay molecules. This leads to a zone of water and ions surrounding the clay particles, known as the diffuse double layer. The particles in the double layer are attracted so strongly to the clay particles that they do not conduct fluids. Fluids go around the soil particle and around the double layer. If the double layer shrinks, flow paths open up, and hydraulic conductivity increases.

1.1.3 **Examples of the Effects of Soil and Water Chemistry on Infiltration**

Agassi et al, 1981, describe a series of tests performed to assess the effects of electrical conductivity of permeant, as well as the ESP, and $CaCO_3$ (calcium carbonate) content of the soil, on infiltration rates. They found that infiltration is more sensitive to the sodicity of soil and electrolyte concentration, than is hydraulic conductivity. They attribute this to the mechanical impact of raindrops, and the relative freedom of particles at the surface to move. Their results are shown in Figure 10.2.

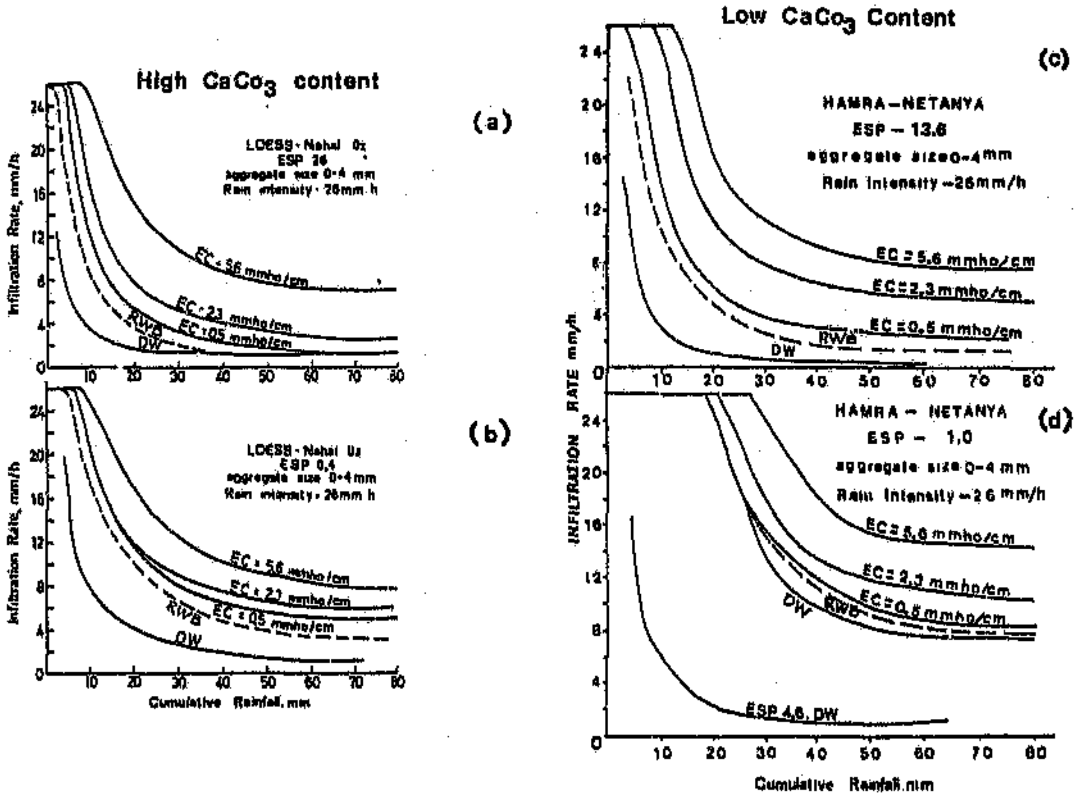

Figure 10.2
The Effects of Calcium Carbonate Content,
ESP, and Electrolyte Concentration on Infiltration (After Agassi et al, 1981)

It should be noted however, that they did use a moderately high intensity of simulated rain (26mm/h) in their tests. According to a study performed by Hudson in Rhodesia in 1971 (cited by Marston, 1982), at rainfall intensities of less than 50 mm/h, the kinetic energy of rain decreases considerably. The kinetic energy of rai· oı intensity 25 mm/h was found to be 90% of that of rainfall of 50 mm/h, while at intensities of 10 mm/h the kinetic energy was found to decrease by a further 30%. At low intensities, the effect of particle movement at the surface would therefore be less important.

The infiltration rates for distilled water and solutions of different hydraulic conductivities of shown. Results for four soils are shown:

- soil with a high $CaCO_3$ content, and a high ESP
- soil with a high $CaCO_3$ content, and a low ESP
- soil with a low $CaCO_3$ content, and a high ESP
- soil with a low $CaCO_3$ content, and a low ESP

An estimation of the curve which would be obtained for RWB water, (based on conductivity) is drawn in.

In all cases an increase in electrolyte concentration was found to decrease infiltrability. It should also be noted that this effect is most marked at low rainfall depths.

In the case of the calcium rich soil, soils of low ESP were more sensitive to the presence of electrolytes than were the soils of high ESP. In soils with low $CaCO_3$ content this trend was reversed. This is attributed to the ability of soils of high $CaCO_3$ content to release electrolytes into permeating water at a rate great enough to prevent clay dispersion.

One would therefore expect the Linbro soil with its low calcium content and high ESP to be fairly sensitive to electrolyte concentration. In fact one would expect it to behave similarly to the soil in figure 10.2 (c). The clay percentage of the soil used in these test is however much higher than that of the Linbro park soil. (11% of 3%) The effects of dispersion in the Linbro Park soil may therefore be less marked.

In summary, based on these results, one would expect that using RWB water rather than rain water would underpredict runoff, and overpredict infiltration,(by as much as 100%.)

A series of ring infiltrometer tests, using both distilled water and RWB water, was performed, in order to try and establish how the behaviour of the Linbro Park soil compares to expectations based on the results of Agassi et al. The tests also yielded information about infiltration rates under ponded conditions.

1.2 The Double Ring Infiltrometer

A double ring infiltrometer with an outer ring of diameter 1m and an inner ring of diameter 0.6m was used. This is smaller than the infiltrometer recommended by the US EPA, (EPA/625/4-89/022, 1989,) but was used because this size of ring was readily available, and easily transportable. The exact method of testing is described in Appendix F.

Four different test sites were used. Tests were performed using distilled water as well as Rand Water Board water. The results are shown in detail in Appendix F, and are summarised in table 10.1, below.

A great difference between the infiltration rates measured on the various sites was found. Steady state infiltration rates vary from 1mm/h to 50 mm/h. Infiltration rates are, in general, very high.

Initial infiltration rates vary greatly from site to site and from test to test. Higher antecedent moistures are generally associated with lower initial infiltration rates, (as would be expected.) This is not, however, always the case. (See the results of tests on site one.)

Steady state infiltration rates for distilled water and for RWB water were similar for a particular site. The difference between results obtained using distilled water, and those obtained using RWB water are not much greater than the differences obtained when repeating tests on the same site, using the same type of water, under the same antecedent moisture conditions. (eg compare the results from test sites two and three.)

Site	Moisture Content	Infiltration Rates (mm/h) for Distilled Water		Infiltration Rates (mm/h) for RWB Water	
		Initial	At 5hrs#	Initial	At 5hrs
One	Natural (2%)	110	30	-	-
One	Drained for 14 days	-	-	20	35
One	Drained Overnight	65	20	25	25
Two	Natural (2%)	-	-	300	50
Two	Drained for 14 days	55	50	-	-
Two	Drained Overnight	70	30	25	35
Three	Natural (2%)	-	-	11	4
Three	Natural (2%)	-	-	4	1
Three	Drained for 2 days	1	1	-	-
Four	Natural (2%)	-	-	600	100
Four	Drained Overnight	-	-	530	50

At 5hrs most of the tests had more or less reached steady state conditions.

Table 10.1
Results of Double Ring Infiltrometer Tests

The very high infiltrability and the large differences between sites is attributed to the presence of cracks in the cover. Many of these cracks are not readily visible on surface (but sometimes show up when wet.)

Site 4 was located on a visible crack. Infiltration rates for site 4 were so great that not enough distilled water could be obtained to run a test on this site. It should be noted that infiltration rates obtained for this site after it had been thoroughly soaked, were much lower, suggesting that the crack in the cover had closed somewhat as a result of swelling of the soil.

These results do not suggest that infiltrability of the cover increases when RWB water is used, (as was expected on the basis of the discussion in section 1.1.) This is again attributed to macroscopic effects.(ie cracks in the cover.) These are obviously far more significant than the micro-chemical effects in the case of this landfill.

On the basis of these test results it was decided that the use of RWB water in the sprinkler infiltrometer tests would not lead to great errors in runoff measurements.

2 SPRINKLER INFILTROMETER TESTS

A sprinkler infiltrometer was designed and built, and runoff during simulated storms, of various depths, was measured. Runoff from three different test plots was measured. Test plots were chosen to have different slopes, degrees of vegetation, and surface cracking.

The design of the infiltrometer, the runoff plots, and runoff measurement systems are described in this section. The results of the tests are compared to runoff predictions made using existing prediction methods.

2.1 Design Depths

Most studies on rainfall depths, have been carried out for the purposes of designing storm water control systems. (eg Adamson, 1981) In this case the heaviest rainfall in a period of years is of interest. In the case of infiltration however, rain typical of an ordinary day is of interest. It is under these conditions that most infiltration takes place.

Likewise most methods for estimating runoff are based on storm events. These methods may therefore be expected to overpredict the percentage of runoff for a rainfall event of very common occurrence.

In order to determine what depth of rainfall the simulator should be designed for, an analysis of daily rainfall from a nearby rainfall station, (with a 30 year record,) was analysed. The results are shown in Figure 10.3 below.

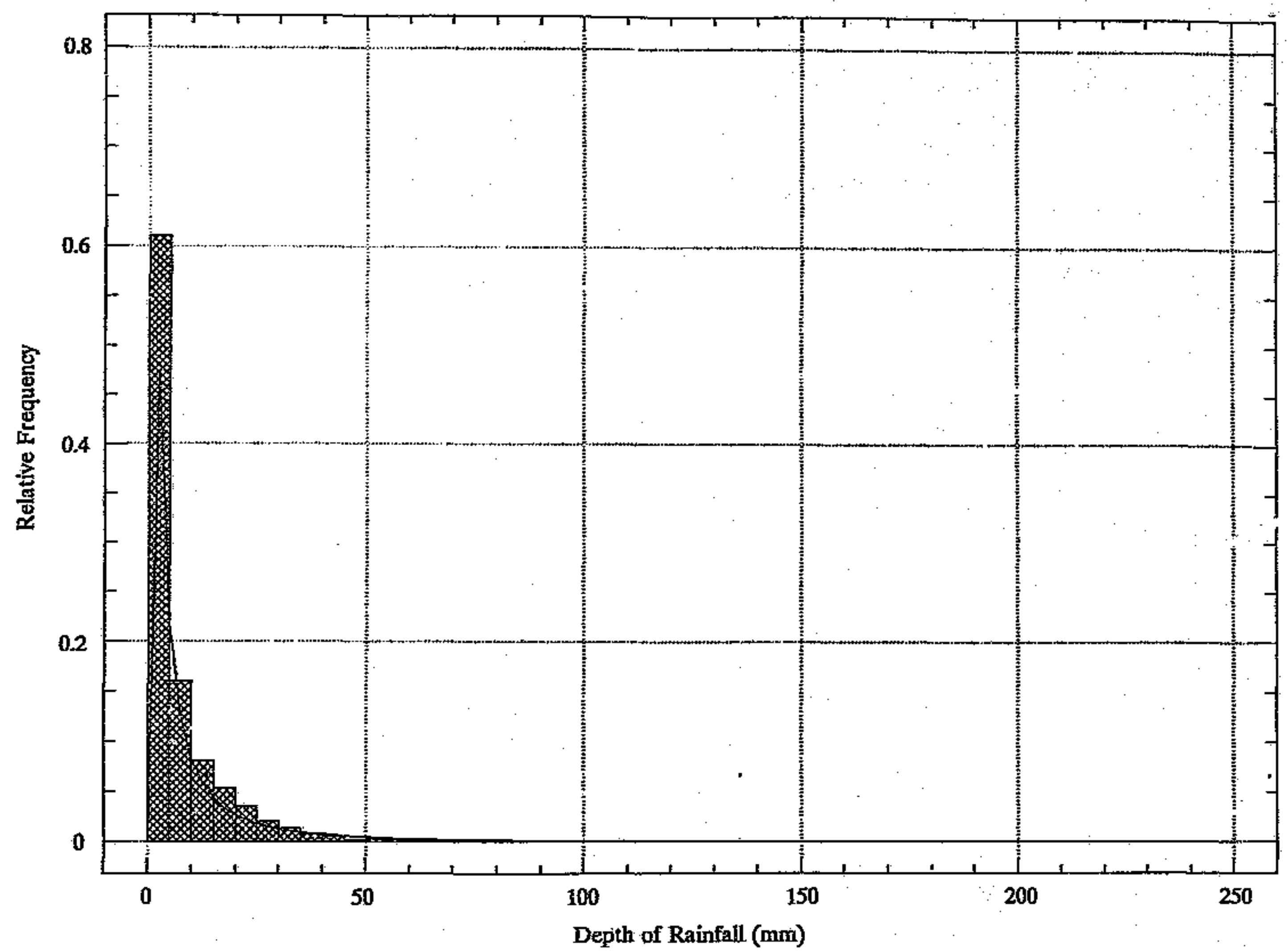

Figure 10.3
Frequency-depth distribution for daily rainfall at Jan Smuts Airport

The figure shows that some 60% of daily rainfall depths are below 5mm. 75% of rainfall events are less than 10 mm in depth, and about 90% of daily rainfall is less than 20 mm in depth. The mean rainfall depth is about 10 mm, with a standard deviation of about 13 mm.

Based on this information it was decided to simulate rainfall events of 5mm, 10mm, and 20mm depths.

The actual rainfall depths achieved were checked by using a number of rain gauges distributed across the site.

2.2 Design Intensities

As is the case for studies on rainfall depths, studies on rainfall intensities are generally geared towards the design of storm water control systems. Depths lower than 20 mm generally do not feature on intensity-depth-duration curves. (eg Schmidt and Schulze, 1987)

As stated in Chapter 4, the SCS rainfall intensity distributions, have been modified for South African conditions. The SCS method may be used to give intensity distributions for any rainfall depth. The distribution obtained may not, however, be appropriate for low rainfall depths, since the distributions are based on storms of 10 to 20 year recurrence intervals. Schmidt and Schulze, 1987 found that for low rainfall depths, the peak rainfall intensity occurs close to the start of the storm, rather than close to the middle of the storm, as is the case with the SCS distributions. The assumption that the peak intensity occurs in the middle of the storm, leads to conservative estimates for stormwater control design, but would tend to underestimate infiltration.

The Johannesburg Municipality have made data from their autographic rainfall gauges available for study in this project. An attempt was made to use this data to try and determine an appropriate rainfall depth-intensity distribution for the site, for low rainfall depths.

The data from their gauging stations has been summarised, showing cumulative depths at times 2; 5; 10; 20; 30; 60; 90; 120; and 180 minutes into the storm. Without analysing the original recording charts it is very difficult to pick out peak intensities from this data. Analysis of the original charts is an extremely time-consuming process. Due to a lack of time, the analysis has not been completed for this project. It is, however, evident from the summarised data that peak intensities do indeed occur at the start of the storm for rainfalls of lower depths. The data also showed that it is also not uncommon for rain to occur in two or three spates during the day, each spate having a peak intensity at the start.

In the absence of more definite information on actual distributions, the SCS storm-distributions were used as a basis for the sprinkler infiltrometer design.

The SCS distributions could not be reproduced exactly, due to constraints of the capabilities of the sprinkler systems, and the impracticalities of testing over a 24- hour period. They were, however, used as a basis for design.

The SCS distributions yield peak intensities of 28 mm/h; 14 mm/h; and 7 mm/h for rainfall events of 20mm, 10mm and 5mm depths respectively. The SCS rainfall intensity distributions for the design storms are shown in Appendix G.

2.3 Infiltrometer Design

Infiltrometers which closely reproduce drop size, kinetic energy, and drop pattern of rainfall have been described in Chapter 7.

The building and calibration of such a device is a lengthy and expensive undertaking, and is beyond the scope of this project.

Investigations into the feasibility of borrowing such a device were carried out. The South African Department Agriculture, Pretoria, have a rotating boom rainfall simulator which irrigates a plot sized 8m by 8m. It is, however, designed to operate only at an intensity of 60mm/h. (Mc Phee, pers. comm., 1991) This may be suitable for erosion studies, but is not (on the basis of information given sections 2.1 and 2.2) suitable for infiltration studies.

The Department of Agricultural Engineering at the University of Pretoria have recently designed and built a variable intensity rainfall simulator. (The cost of materials for the system being about R 10 000.) It, however, irrigates a plot of dimensions 1m by 0.6m. (La Grange, pers. comm. 1991) This is considered to be too small to adequately represent surface conditions on the landfill.

Existing simulators which might be available to use in infiltration studies are therefore unsuitable with respect to either intensity, or size of plot irrigated.

It was therefore decided that it would be most appropriate to design a cheap, simple, easily portable system which would be capable of reproducing rainfall intensities required for this study. Attention has not been paid to kinetic energies and drop sizes. (These parameters are likely to be of less importance if low rainfall intensities are to be simulated, than they would be if high intensities were to be simulated.)

The simulation system which was chosen is a simple irrigation system, using rotating sprinklers. The cost of materials for the system was about R 3 000.

2.3.1 The Sprinklers and Nozzles

A wide variety of sprinklers, with different nozzles has been tested by the South African Department of Agriculture. The Department publishes irrigation distributions using various flow rates, pressures, and spacings, for each sprinkler type. The 'coefficient of uniformity' (which describes the degree of uniformity of irrigation achieved) is computed for particular sprinklers, nozzles, flow rates, pressures, and spacings. A coefficient of uniformity above 80% is regarded to be acceptable for agricultural irrigation purposes , while a coefficient of uniformity of above 84% is regarded to be good, and a coefficient of 90% is considered to be excellent. (Reinders, pers. comm., 1991)

It should be noted that these tests are carried out under windless conditions. Wind can severely affect distributions. It should also be noted that evaporation is minimised in the tests so that actual application rates achieved in the field may be much lower than indicated by the tables published by the Department of Agriculture.

An example of the test results for sprinklers is given in Appendix H. A graphical representation of water applications of various coefficients of uniformity is also given.

A 'Dusi R & N 71' sprinkler was selected to deliver the required application rates. The sprinklers are capable of irrigating an area large enough to represent the behaviour of a landfill surface during rainfall. An area of between 80 m^2 and 320 m^2 can be uniformly irrigated using 4 sprinklers only. The Dusi is a hammer driven sprinkler. Other sprinklers which are not hammer driven apparently give more uniform distributions. These are however, not obtainable in South Africa at present.

The minimum reasonably uniform application rate achievable using agri 'tural sprinklers is 3mm/h. The maximum rate which can be achieved using one set of sprinklers is about 20 mm/h. (Doubling the number of sprinklers in a given spacing could double this r

These limits, together with the computed SCS distributions, were used to design an intensity-duration distribution for each of the rainfall depths selected for simulation. The practicalities of the length of testing time were borne in mind also. Due to the limitati the sprinkler system, a stepped distribution was used. It w decided that no more than four different sprinkler spacings, and no more than two different nozzle combinations were to be used for the tests so as to avoid confusion. The combinations of nozzles, sprinklers, and spacings used to achieve the different intensities are given in Appendix G. The idealised SCS distributions, as well as the distributions designed for the sprinklers, are shown in Appendix G.

2.3.2 The Pump

The sprinklers selected for the test require a pressure of between 250 kPa and 350 kPa in order to operate. Flow rates of between 4 m^3/h and 7 m^3/h were required to deliver the correct irrigation intensities to the plots. A petrol driven, centrifugal, portable pump capable of delivering a maximum head of 600 kPa, and a maximum flow rate of 24 m^3/h was used. The pressure-flow rate curve for the pump is shown in Appendix J.

2.3.3 The Water Supply

Total volumes of water of 6.6 m^3; 10.4 m^3; and 16 m^3 were required to simulate storms of design depths 5mm; 10 mm; and 20 mm respectively. RWB water was available on the landfill site, but the supply point was located some 500m away from the actual test plots. This supply point also had to supply the needs of every day water use on the site. Pumping directly from the supply point was thus precluded. A portable, 6m^3 reservoir, made of High Density Polyethylene was used as a reservoir from which to pump. The reservoir was refilled periodically by a water tanker provided by Johannesburg Municipality. The water supply system is shown in Figure 10.4

2.3.4 Delivery System

A rotameter type flow meter was fitted to the pump outlet so that delivery to the sprinklers could be measured. The flowmeter was calibrated in the laboratory, using a container hanging from a very large spring balance. A gate valve was included before the flowmeter, so that the flow could be regulated. The pump speed can also be altered to vary the flow rate.

After passing through the flow meter, the water stream was divided into four, through a series of tee pieces and elbows. 50 mm diameter low density polyethylene piping supplied each of the sprinklers. Pressure meters were installed at each sprinkler head to ensure that correct delivery pressures were obtained. The pressure meters were individually calibrated in the laboratory. The sprinklers were mounted on stands, at a height of 1m above ground level.

Figure 10.4
Water Supply System for Rainfall Simulations

2.4 Interception and Irrigation Losses

In the tests, an estimation of infiltration was made, chiefly by measuring runoff. It was impossible to measure interception losses as described in Chapter 4, since the grass had been mown short. (The tests were performed at the end of the dry season.) This would in any event have minimised interception losses. The grass on one of the test sites was accidentally burnt in a grass fire before the tests were performed. The results obtained from this site would therefore represent minimum interception losses.

Rain gauges were positioned at various points on to ensure that a reasona even application of water was achieved. On sunny days the rain gauges collected, on average only about 70% - 75% of the design storm depth. The loss is thought to be due partly to the evaporation of water as it left the sprinklers. Two tests were conducted on a cold, cloudy day. On this day the 'effective irrigation' was found to be between 80% and 90% of the design rainfall depth.

The raingauges were fitted with covers. Droplets collecting on the covers would tend to evaporate before falling into the gauge. Part of the difference between the depth of water collected by the raingauges, and the designed irrigation depth may therefore represent evaporation from intercepted water. Evaporation from intercepted water would of course be higher during the tests than in a real rainfall event, since the humidity of the air is much greater during natural rainfall.

Based on SCS estimations of initial abstractions under wet antecedent moisture conditions, the interception losses during natural rainfall (of a depth of 20mm) would be about 15%. It can therefore be assumed that the balance of the losses (10% to 15%, on average) are due to evaporation as the water leaves the sprinklers, and increased evaporation of intercepted water under conditions of low humidity.

2.5 The Runoff Plots

A runoff plot size of 9m x 9m was used. The plot size was chosen to be large enough to be representative of surface conditions of the landfill. The size of the plots was influenced by sprinkler spacings required to give chosen intensities of simulated rainfall, as well as the practicalities of water supply.

In all cases the area actually irrigated was larger than the runoff plot. This was necessary to achieve a uniform distribution over the runoff plot itself.

Plots of different slopes, degrees of vegetation, and surface cracking were chosen. Each of the chosen plots was surveyed in some detail so that a good idea of the slopes and minor surface features was obtained. The choice of the plots was facilitated by a tachy survey of the entire test area. The plots were located as close as possible to the edges of the landfill, so as to facilitate runoff collection (Runoff collection is discussed in more detail below.) Each of the plots is described briefly below.

Test plot 1: Plot 1 has an average slope of 1.7%, and has a vegetation coverage of roughly 75%. One corner of the plot lies in a slight depression, and is thickly vegetated. At the time when the tests were conducted, no cracks were visible on the surface.

Test plot 2: Plot 2 has an average slope of 1.6%, and has a vegetation coverage of about 50%. A nu... of large cracks, up to 10 mm wide were visible on the surface at the time of the tests.

Test plot 3: Although normally densely vegetated, at the time at which the tests were carried out, this plot had been burnt completely. No evidence of cracks was present on the surface. The average slope of the plot is 20%. The slope is slightly terraced. The slope was obviously constructed in this manner to facilitate the establishment of vegetation.

Although the test plots had an overall slope, some small depressions were present on all of them.

2.6 Runoff Collection System

Small furrows, about 50 mm deep and 100 mm wide were dug around the edges of each plot. 100mm diameter PVC half pipe channels were placed in the furrows, at an angle such that they diverted water running onto the plot from upslope; and intercepted water running off the plot, channelling it towards the lowest corner of the plot. The edges of the PVC 'gutters' were sealed with gypsum.

A hole some 300 mm x 300 mm in plan, and 200mm deep was dug at the lowest corner of each plot. A watertight steel box was placed in each of these holes. The gutters around the edge of the plot were arranged to feed into the box. A 50 mm diameter low density polyethylene (LDPE) pipe was fitted at the bottom of each box. Water flowing into the boxes was thus conveyed to the runoff measurement system.

The runoff collection and measurement system was sized on the basis of SCS runoff predictions, taking into account also the results of the ring infiltrometer tests.

The maximum amount of runoff predicted for the design storms by the SCS method was 6.5 mm, (or 0.5 m^3 for the chosen plot size.) Three 200 litre drums would be required to collect this volume of water. To install three 200 litre drums at the edge of each plot would have involved digging three holes about 1m deep, and 1.2m in diameter. This was not at all desirable. The drums were therefore located on the slopes of the landfill, and runoff was fed into them by the LDPE pipes.

The 200 litre drums were fitted with a transparent riser pipe or sight tube on the outside of the drum, and a length of tape measure was fitted next to this. In this way the water level in the drum could be easily read.

It would have been preferable not to route the runoff down a pipe, since a better idea of runoff rates from the plot could then have been obtained.The whole system was primed before the runoff tests commenced so that theoretically, the moment a drop of water entered one of the gutters, another drop would flow out of the pipe into the drum. Practically however, there appeared to be some lag in the response of the drum, especially where longer runoff pipes were used.

Consideration was given to using a V-notch weir for measuring runoff rates. Calculations showed, however, that the smallest runoff rate that could be measured by the system would be 15 mm/h. Expected runoff rates were very much lower than this. It was therefore decided to use collection drums.

The runoff collection system used is illustrated in figure 10.5.

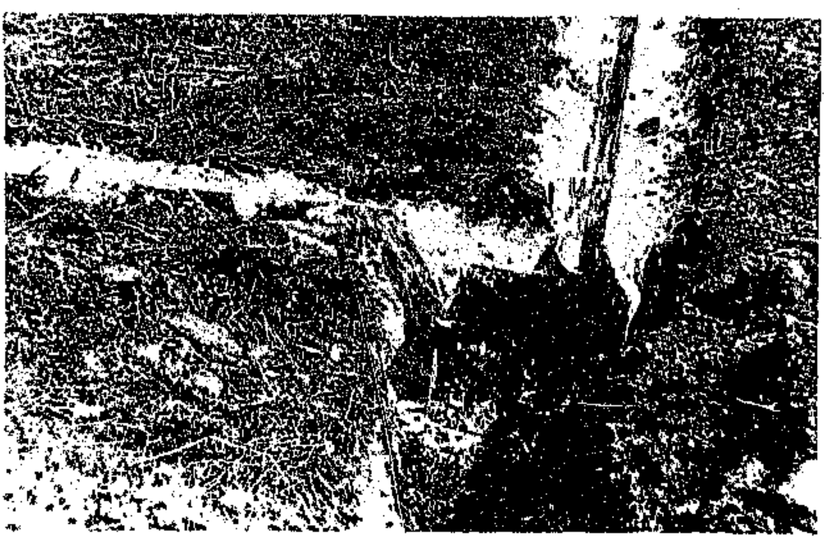

Figure 10.5
The Runoff Collection System

2.7 Predicted Runoff

Based on the high infiltration rates measured during the ring infiltrometer tests, (about 35 mm/h on average, at steady state), and considering that the maximum simulated rain intensity was to be 20mm/h, no runoff was expected for the design storms.

The rational method, however, predicts 11% runoff for all rainfall depths for the landfill. (Hojem, 1988)

Table 10.2 shows predictions made using the SCS method, adapted for South African conditions. The cover soil was taken to belong class B (moderately low runoff potential) on the basis of textural classifications. Predictions for the design rainfall depths, as well as for the measured rainfall depths, are given. As pointed out in section 2.4, the 'effective' irrigation depth achieved during the tests lies between these two figures. One could therefore expect measured runoff depths to lie between the two sets of predictions.

Figures for poor grass cover, fair grass cover, and good grass cover are given. The predicted percentage runoff decreases within increasing vegetative coverage. Figures for different antecedent moisture conditions are also given, the predicted percentage of runoff increasing with increasing soil moisture. The SCS method does not take the effect of slope into account in predicting volumes of runoff.

The disadvantag of using both the SCS and the rational methods for predicting infiltration volumes, is that they predict runoff, rather than infiltration. In order to predict infiltration volumes using these methods, an estimation of interception losses also needs to be made.

Ideally, a prediction of infiltration using Richard's equation should be included for comparison. Time constraints, and the lack of a clearly defined suction-moisture content curve for the cover material, have precluded this.

The runoff predictions are compared to the results of the field tests in section 2.8.

DESIGN RAIN DEPTH				EFFECTIVE			
	% Runoff for Antecedent Moisture Condition 1	% Runoff for Antecedent Moisture Condition 2	% Runoff for Antecedent Moisture Condition 3		% Runoff for Antecedent Moisture Condition 1	% Runoff for Antecedent Moisture Condition 2	% Runoff for Antecedent Moisture Condition 3
Depth	Poor Grass Cover			Depth	Poor Grass Cover		
Initial Abstractions	80%	30%	15%	Initial Abstractions	80%	30%	15%
5 mm	0.1%	3.5%	11%	3.5 mm	0.1%	2.5%	8%
10 mm	0.3%	6.5%	20%	7.5 mm	0.2%	5%	16%
20 mm	0.5%	12%	32%	15 mm	0.4%	9.5%	27%
Depth	Fair Grass Cover			Depth	Fair Grass Cover		
Initial Abstractions	105%	60%	15%	Initial Abstractions	105%	60%	15%
5 mm	0%	0.7%	7%	3.5 mm	0%	0.5%	5%
10 mm	0%	1.4%	13%	7.5 mm	0%	1%	11%
20 mm	0%	2.6%	22%	15 mm	0%	2%	27%
Depth	Good Grass Cover			Depth	Good Grass Cover		
Initial Abstractions	110%	80%	30%	Initial Abstractions	110%	80%	30%
5 mm	0%	0.1%	3.5%	3.5 mm	0%	0.1%	2.5%
10 mm	0%	0.2%	6.5%	7.5 mm	0%	0.2%	5%
20 mm	0%	0.5%	12%	15 mm	0%	0.3%	9.5%

Note: Initial abstractions for rainfall depths lower than 20mm are not given by Schmidt and Schulze, 1987. All calculations are therefore based on percentages for a rainfall depth of 20mm.

Table 10.2
Runoff Depths Predicted by SCS Method

2.8 Results of sprinkler Infiltrometer tests

In total 10 different runoff tests were conducted. Each of the three design storms was applied to each test plot. The initial moisture content of the surface layer was measured before each test so that an idea of the effect of antecedent moisture could be obtained. The tests were conducted at the end of the dry season. The antecedent moisture of the cover was therefore low. A low antecedent moisture condition is probably representative of conditions before the majority of rainfall on the Witwatersrand.

For the tenth test, a 5mm rainfall simulation was carried out after the surface of the site had been saturated, (ponds were allowed to dry up before the test however.) The results of the tests are given in Appendix K, and are summarised in table 10.3 below.

Infiltration depths were estimated using the measured pumping rate, the measured runoff depths, estimated interception losses, and the depth of rainfall collected in the raingauges. Infiltration rates were estimated in a similar manner.

2.8.1 Infiltration and Runoff Rates

Despite the high infiltration rates measured using the double ring infiltrometers, runoff was measured under application rates of as low as 4 mm/h in the sprinkler infiltrometer tests. Runoff under these low application rates was measured on the falling limb of the hyetograph, ie after the surface of the tests plot had been thoroughly wet.

Recorded runoff rates were low, the maximum recorded runoff rate being 4 mm/h (during an application rate of about 16 mm/h). Runoff rates were not found to increase with increasing slope, (in line with the SCS predictions.) In fact the lowest percentages of runoff were generally associated with the steepest slope. This result, may however, be misleading, since the slight terracing of the slope probably affected the result. A different result may very well be obtained for an unterraced slope.

Plot	Antecedent Moisture Content (m/m)(%)	Average Slope (%)	Veget-ation	Visible Cracks	Estimated Effective Simulated Rainfall Depth (mm)	% Runoff *		Maximum Estimated 'effective' Application Rate (mm/h)	Minimum Estimated Infiltration rate (mm/h) associated with runoff	Maximum Estimated Infiltration rate (mm/h)	Maximum Runoff Rate Recorded (mm/h)	Ponding
						Measured	SCS Prediction					
One	2%	1.7%	75%	No	4.1mm	0%	0%	4	none	3.5	0	no
	14%				4.1mm	1.7% - 1.2%	5% - 7%	4	3.4	3.5	0.8	no
	2%				8.3mm	0.4% - 0.3%	0%	8	7	7	0.2	no
	2%				16.1mm	2.5% - 1.8%	0%	16	4.7	13	1.0	yes
Two	2%	1.6%	50%	Yes	4.1mm	0%	0.1%	4	none	3.5	0	no
	2%				8.3mm	0.3%-0.2%	0.2%-0.3%	8.1	7	7	.01	no
	2%				16mm	4.7%-3.8%	0.4%-0.5%	16	1.8	14	4	yes
Three	1%	20%	100% burnt	No	4.1mm	0%	0.1%	4	none	3.5	0	no
	1%				8.3mm	0.4%-0.3%	0.2%-0.3%	8	2.1	7	0.04	no
	2%				18mm	0.8%-0.7%	0.4%-0.5%	18	2.7	18	0.15	yes

* A range of runoff percentages is given. The first figure is the runoff as a percentage of the rainfall depth measured in the rain gauges. The second figure is the runoff as a percentage of the design rainfall depth. The true figure lies between these two.

Table 10.3
Summary of Results of Runoff Tests, Using sprinkler Infiltrometer

Infiltration rates as high as 18 mm/h were estimated from measured data, despite the fact that runoff was recorded at estimated infiltration rates as low as about 2 mm/h. It should however be noted that high infiltration rates were found to occur on the rising limb of the hyetograph, while runoff associated with low infiltration rates was found to occur on the falling limb of the hyetograph.

It was only during the storms of design depth 20 mm and under application rates of 16 mm/h that ponding occurred.

2.8.2 Antecedent Moisture Conditions

It was only on a design storm depth of 5 mm that the effect of different antecedent moisture conditions was tested for. No runoff was recorded for any of the simulated rain storms of 5mm depth, having low antecedent moisture conditions. In this case the SCS runoff predictions were in good agreement.

In the case of the simulated rainfall event of 5 mm depth, under wet antecedent surface moisture conditions, however, the SCS underestimates runoff by a factor of 3 to 6 times. This corresponds to an error of 2% to 5% of the total rainfall depth. Considering the degrees of inaccuracy of measurements of other aspects of the water balance, this error is not very large. In any event, if the entire depth of the cap were wet (rather than the top 50 mm), a higher percentage runoff may have been recorded.

2.8.3 Vegetation, Surface Cracking, and Slope

The SCS method predicted zero runoff for 5 mm, 10 mm, and 20 mm rainfall depths for plot 1, (with fair vegetation coverage,) under dry antecedent moisture conditions. This prediction was very good for the 5 mm and 10 mm rainfall event. (0% and 0.35 % runoff were measured for these storms, respectively. About 2% runoff was recorded for the 20 mm event. Given the inaccuracies in estimation of other aspects of the water balance, this error may be considered to be small.

The SCS method predicted higher percentages of runoff for plots 2 and 3, which are poorly vegetated.

Percentages of runoff measured for plot 2 were indeed higher, despite the presence of large visible cracks on surface. Percentages of runoff predicted for the 5 and 10 mm events for plot 2 were accurate. Percentages predicted for the 20 mm event, however underpredicted measured runoff by about 10 times.[#] Although the prediction was out by a factor of 10, this represented an error of only 3.5% to 4% of the rainfall depth.

Percentages of runoff predicted for plot 3 were very close indeed to the measured runoff, the maximum error being 0.4% of the rainfall depth. It was expected that due to the fairly steep slope of this plot the runoff recorded would be higher. The lower percentage runoff recorded is attributed to the presence of terracing and the fact that the surface of this plot is less compact than that of plots 1 and 2.

2.8.4 The Rational Method

The prediction of the rational method of 11% runoff correlates fairly poorly with measured runoff rates. It was found to be in error by between 6% and 11% of total rainfall depth, for the simulations carried out in this project. Assuming a constant, but lower runoff factor (say 2%) for the rational method, based on these test results would improve the accuracy of predictions for the low depths of rain, but is likely to be erroneous for higher depths of rain.

In general the SCS predictions were found to be surprisingly accurate. The presence of the surface cracks did not seem to have a noticeable effect on runoff percentages under the simulated rain conditions, despite the fact that very high infiltration rates were recorded under the ponded conditions of the double ring infiltrometer. Under heavy

[#] This result may have been influenced by an operating error which occurred during the simulation. Although a total depth of 20 mm was applied, the intensity distribution was accidentally altered, causing the peak rainfall intensity to be skewed towards the start of the storm.

rainfall, when water tends to pond, infiltration may perhaps be higher than predicted by the SCS method. It is, however, noted that some ponding did occur during the heaviest rainfall simulations, and in these cases, the runoff predicted by the SCS method was in fact lower than the measured runoff.

Although the runoff predictions are good to within a few percent of the rainfall depth, the infiltration cannot be estimated with such certainty, because estimations of interception losses are less accurate, (probably to within 10% to 15%.) A better estimation of interception losses would be valuable in estimating infiltration. It would be of interest to perform runoff tests during the growing season, when the grass on the site is taller, and interception losses are higher.

Although the data gathered during these tests indicates that the SCS method gives good predictions of runoff, for this case, the data is too sparse to draw any general conclusions about the degree of accuracy of SCS predictions for landfill surfaces. In order to draw more general conclusions, more testing, on different sites would have to be carried out.

It would be valuable to measure runoff during some real rainfall events, to check on how the simulator results compare with real rainfall conditions.

An investigation into rainfall depth-intensity distributions for low rainfall depths would be useful. The effect of a peak rainfall intensity close to the start of the rainfall event should also be investigated. The effects of antecedent moisture conditions on runoff from landfill surfaces, and the general state of the antecedent moisture prior to rainfall could be investigated further.

It would also be valuable to compare the results of the runoff tests to infiltration predictions made by Richard's equation.

CHAPTER 11

IN-SITU WATER CONTENT AND SUCTION MONITORING IN UPPER LANDFILL LAYERS

Changes in moisture content of the cover layer, and the upper layers of refuse were investigated to acquire more knowledge about soil-moisture movement and evapotranspiration in the upper layers of a landfill.

The depth to which moisture may be drawn out by evapotranspiration, compared to the depths of roots within a landfill was of interest. The assumption that the refuse blocks capillary movement of moisture, and that no moisture is therefore returned to the atmosphere, through the cover, after it has reached the refuse, was to be investigated. The speed of moisture movement within this zone, was also of interest.

1 THE APPARATUS

A number of methods of monitoring in-situ moisture contents have been described in Chapter 7. Calibrations for two of these methods (psychrometric and filter paper techniques) are given in Appendix E. The results of the calibration showed that it would be most appropriate to use psychrometers for the field tests. Provision was, however, made to use the filter paper technique as well.

Although the primary aim of the tests is to monitor in-situ moisture contents, the techniques chosen actually measure suction. Theoretically if the suction is known, the moisture content can be deduced. Attempts to measure a suction moisture-content curve for the cover have been described in Chapter 8. The great degree of scatter obtained in these tests makes it difficult to relate suctions to moisture contents. Furthermore, no suction-moisture content curves for refuse have been measured in this project. It is therefore difficult to use suction data to do a water balance for the upper landfill layers. A good qualitative idea of moisture movement may, nevertheless be obtained from suction measurements as suction is the driving force for moisture movement.

1.1 Design of Apparatus

It is desirable to install the suction measuring devices with minimum disturbance of the profile, as disturbing the profile changes its moisture-suction characteristics. A method of installation which allows for easy recovery (for inspection, replacement, and cleaning of the instruments) is preferable. A system for installing psychrometers in the upper layers of landfills, which meets these requirements was devised. The scheme is described below.

A small diameter hole was drilled through the cover and upper refuse layers. The instruments were installed in this hole by mounting them on a rod which extends down the entire depth of the hole. The instruments were 'stacked' above one another within the hole, to maximise the number of readings taken within a profile. A cell isolating each instrument from the next is provided so that suction conditions do not equilibrate throughout the depth of the hole. Suction conditions at a particular level in the surrounding refuse profile, are allowed to equilibrate with suction conditions within a cell of the hole. The suction can then be measured by the psychrometer installed in the cell.

The hole is lined with a plastic pipe, perforated at intervals corresponding to the depths at which the suction is to be measured. The walls of the pipe form part of the isolating cell. The horizontal walls of each cell consist of discs of soft rubber, (of the same diameter as the plastic pipe,) which are mounted between two steel plates (of diameter slightly smaller than that of the plastic pipe.) The diameter of the rubber seal can be increased by tightening two bolts, located on either side of the steel plates, so ensuring a good seal against the PVC pipe. The psychrometer is mounted between a pair of these seals.

A hole is left in the plates to allow the psychrometer leads to pass to the surface. This enables the psychrometers to be operated from the surface. These holes are sealed with silicone rubber sealant once the psychrometer stack has been assembled.

The cell walls also prevent the psychrometer head from getting wet. (Once a psychrometer head has been wet, it may begin to corrode, and no longer give accurate readings.)

The system is illustrated in Figures 11.1 (a) and (b). Figure 11.1 (a) shows how a perforated plastic container may be placed within the cell to hold strips of filter paper, (so that the filter paper technique may also be used.) The filter paper could be retrieved in order to take readings, by extracting the rod from the hole.

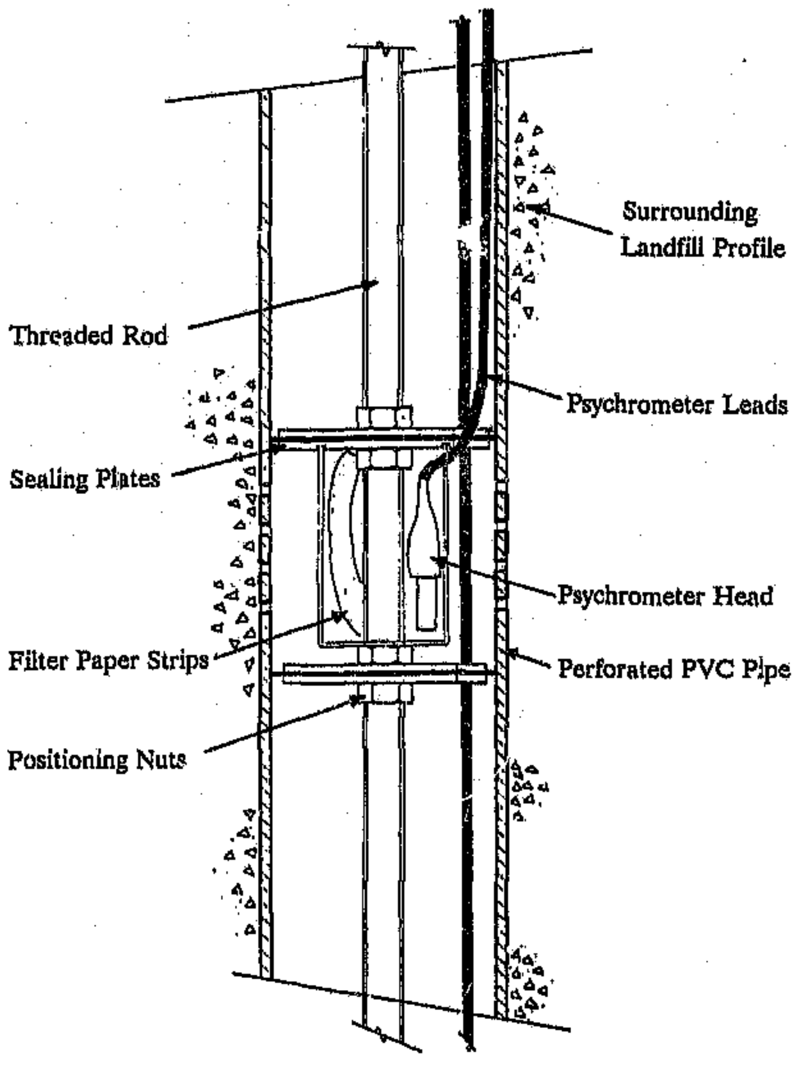

Figure 11.1 (a)
Device for measuring in-situ suctions: Perforated pipe, horizontal cell walls, position of psychrometer head, and provision for using filter paper technique are illustrated.

Figure 11.1 (b)
A 'psychrometer stack'

1.2 Installation of Apparatus

Four sites for monitoring suction were selected. A 'psychrometer stack' was installed on each of the three runoff test plots, and a fourth one was installed on a 'control' plot, which was not subjected to rainfall simulations. The holes were drilled, and logged and then the exact spacing of the instruments was decided on, according to conditions encountered in the hole.

The holes were drilled using an petrol driven concrete coring machine. A 100 mm diameter diamond tipped core barrel was used. The material from the hole was not flushed with water, so as not to disturb in-situ moisture contents. The drilling was done slowly and the material was generally soft so the core barrel did not need to cooled.

The material from the hole generally stuck inside the core barrel. The core barrel was lifted at intervals, the material was retrieved from the barrel, and the profile of the hole was logged.

The drilling process is illustrated in figure 11.2.

Figure 11.2
Drilling Holes for In-situ Suction Measurements

The stratigraphic profiles of the monitoring holes are given in Appendix L.

The holes were drilled to the depth at which they refused.* (This appeared usually to be a chunk of concrete, or a really thick piece of steel. Pieces of steel up to 2mm in thickness were successfully drilled through.)

The holes were then covered for a day while the perforated PVC pipes which line the holes were prepared. (The spacing of the perforations was decided on according to conditions found in the hole.) The 60 mm diameter perforated pipes were then placed in the 100 mm diameter hole, leaving a space of 20 mm around the pipe. The profile of the upper layers was then reconstructed in this space, using material that had been extracted from the hole. It was compacted back into the hole using a rod, ensuring a good fit between the hole and the surrounding material.

Although the profile at the edge of the pipe was disturbed, the disturbance was kept to a minimum. Since suction, rather than moisture content is to be measured, the effect of this disturbance should not influence results significantly.

A small concrete cap was placed around the top of the pipe, ensuring that water would not run into the pipe, or down the side of the pipe. The cap was kept small so as to not to prevent evaporation from the adjacent profile.In addition, bentonite seals were placed in the reconstructed portion of the profile, at levels between psychrometers, so as to discourage moisture from short-circuiting through the disturbed part of the profile.

1.3 Problems Encountered

It has been difficult to keep the temperature gradient between the heads of the psychrometers, and the leads on the surface, low enough to prevent temperature influences from interfering with readings. A sheet of polystyrene foam placed over the

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* Although a diamond tipped core barrel was used, very hard material could not be drilled through. This was because the rig could not be secured to the ground very well, and the weight of the rig alone could not apply enough pressure to enable the drill to bore through the hard material. In any event, drilling through very hard material would have caused the core barrel to heat up. The use of water to cool the barrel was not desirable, since it would have affected moisture contents.

installation has kept the temperature differences reasonable. It has been found to be important to take readings early in the morning when temperature gradients are at a minimum.

The psychrometers have been in-situ for about four months at present, and have worked reasonably well. Some of them are now beginning to give trouble. It is suspected that the heads of the psychrometers may be corroding, or may have become contaminated by condensate from landfill gas. They will be retrieved and inspected.

2 RESULTS OF SUCTION MONITORING

The psychrometers were read about once a week, using a Wescor PR-55 control box. A standard cool time of 15s, and a cool current of 8mA was used. The control box was connected to an x-t recorder, so that the output from each psychrometer could be analysed. The results of the suction monitoring are shown in figures 11.3 - 11.6.

Monitoring started towards the end of the dry season. The suction in most of the holes was high at this stage, indicating (as would be expected) that the moisture contents in the upper part of the landfill profile were low.

Suction changes show similar trends in all the holes. The profiles tend to dry up (to their full depth) during hot, dry weather, and wet up (to their full depth) after rain, (or after simulated rain.)

The fact that different suctions were obtained throughout the profile indicates that the seals between psychrometers were working.

The results of the suction monitoring for each plot are discussed below.

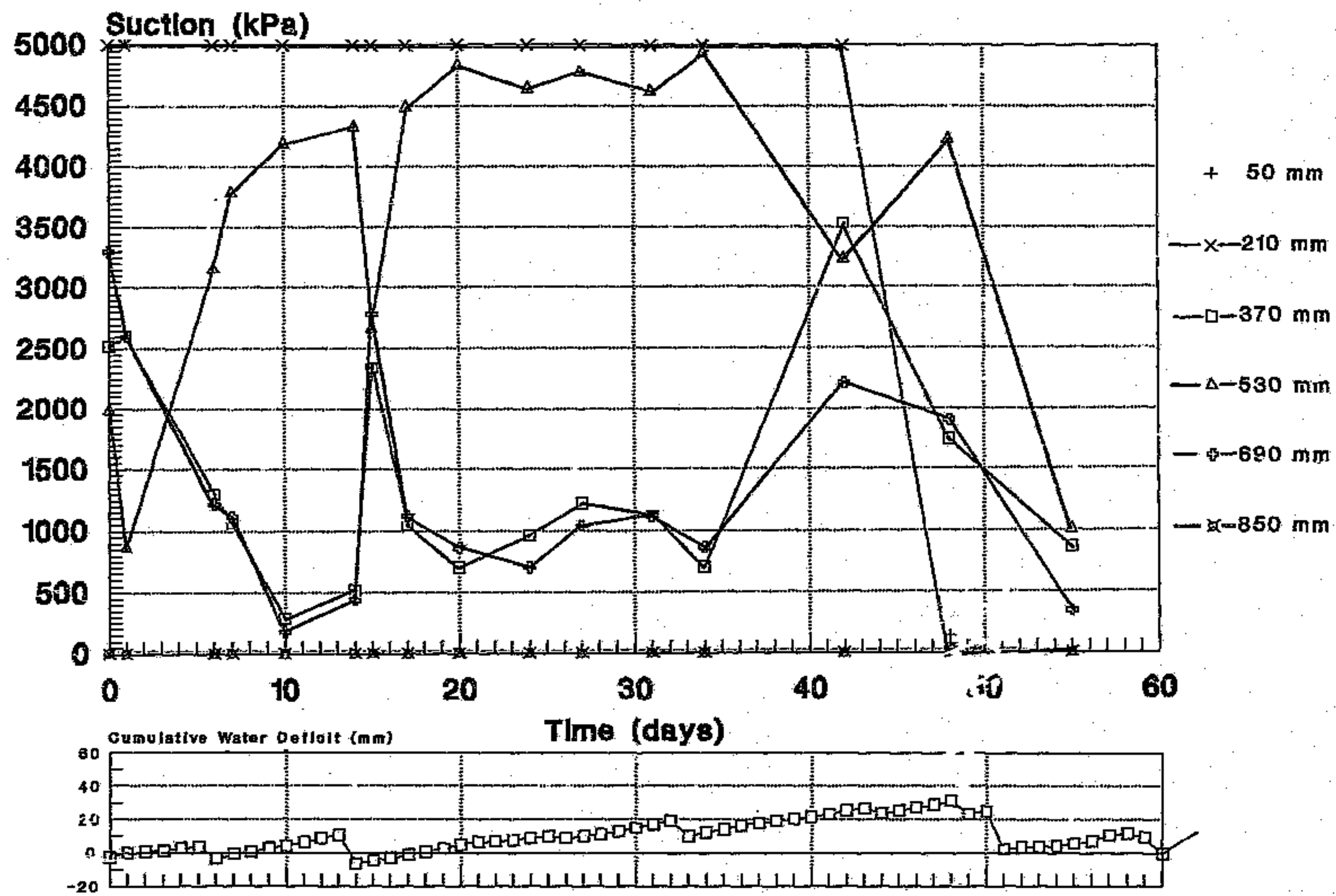

Figure 11.3
Results of In-situ Suction Monitoring - Plot 1

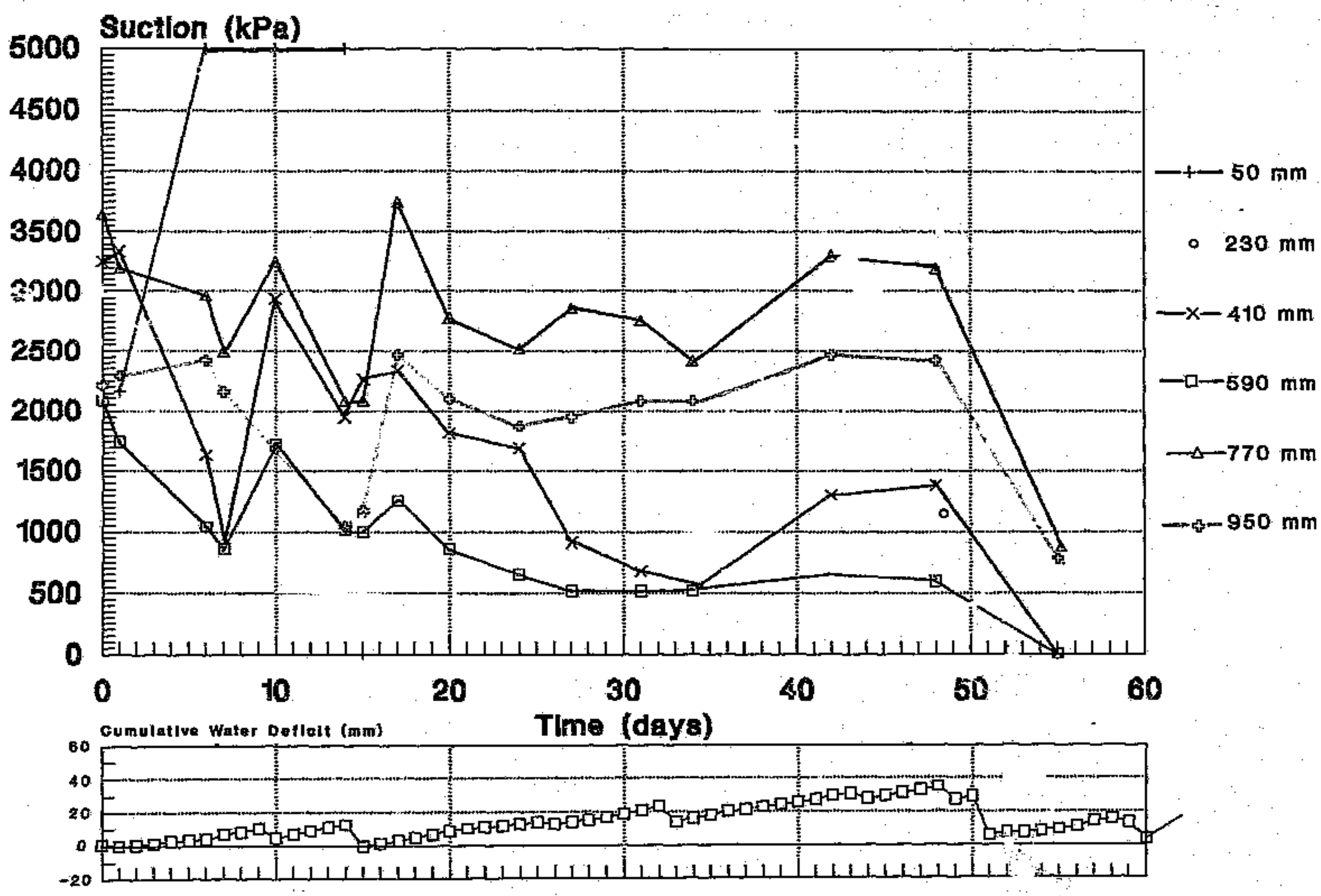

Figure 11.4
Results of In-situ Suction Monitoring - Plot 2

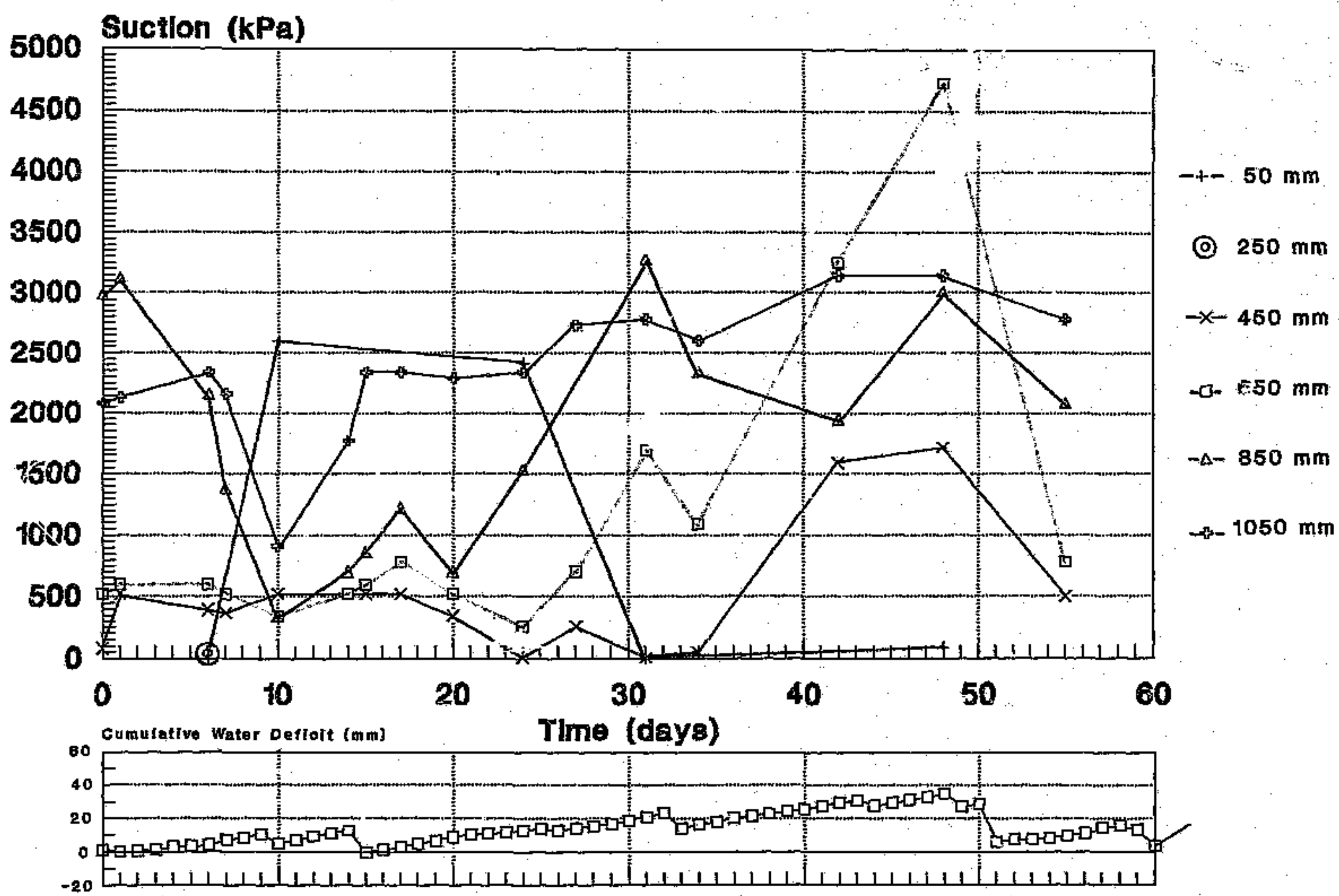

Figure 11.5
Results of In-situ Suction Monitoring - Plot 3

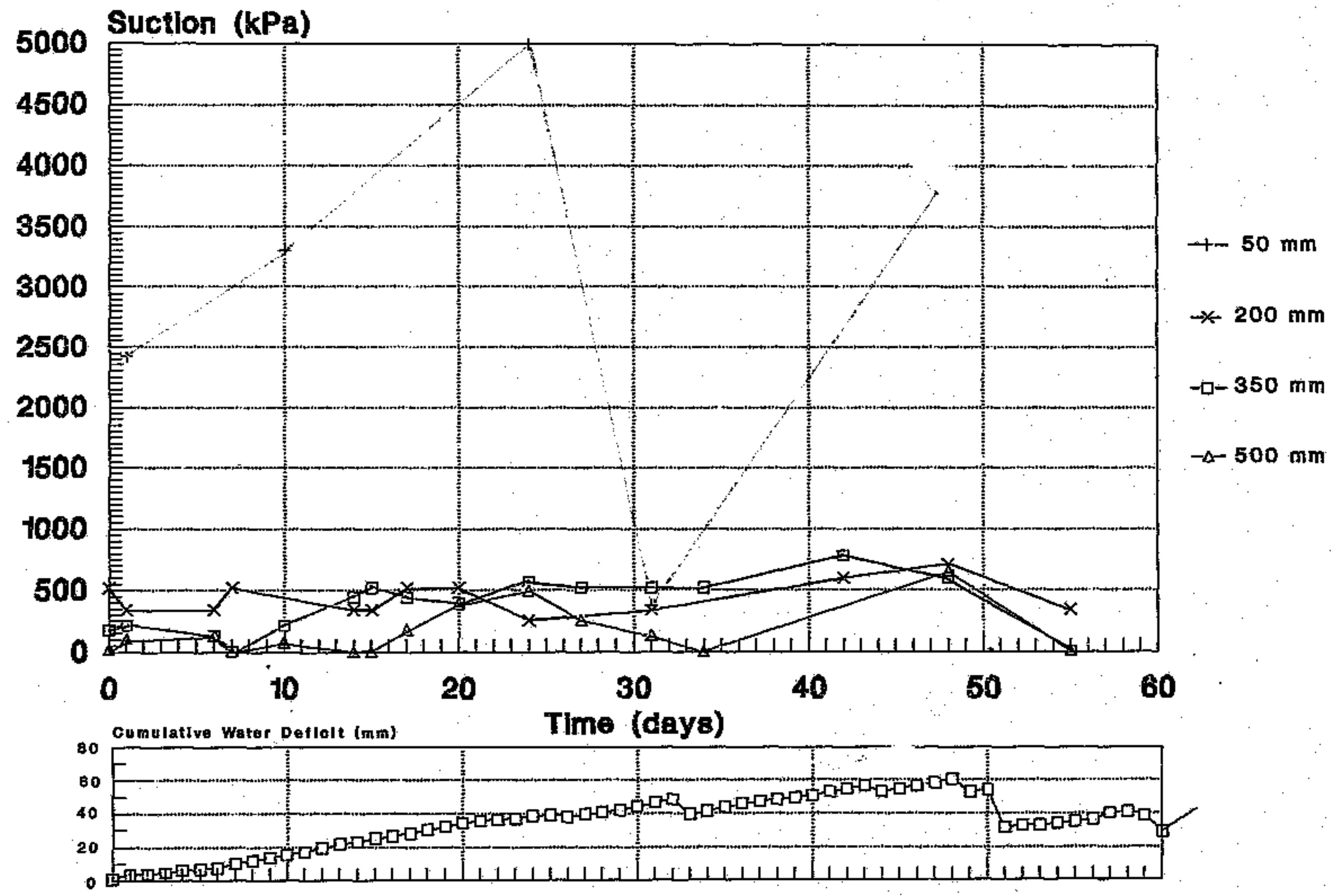

Figure 11.6
Results of In-situ Suction Monitoring - 'Control' Plot

2.1 Plot 1

Six psychrometers, spaced evenly, to a depth of 850 mm were used in the hole on this plot. The cover was found to be 450 mm thick here. Three of the psychrometers were therefore located in the cover layer, while the remaining three were located in the refuse profile.

Depth 50 mm (cover material) - The psychrometer placed at a depth of 50 mm has very rarely given useable readings. This is due to thermal gradients, which cause errors in the psychrometer output.

Depth 210 mm (cover material) - The suction conditions at this depth were usually too high (greater than 5000 kPa) to be determined by psychrometric techniques. Only after fairly heavy rainfalls, were suction conditions within range of the psychrometer.

Depths 370 mm (cover material) **and 690 mm** (refuse)- Very similar readings were obtained for these two layers, although they are separated by a zone in which the suction was found to be much higher. The suction in these two layers was found to drop within about four days of rainfall. During dry spells, the suction rises indicating that the profile is drying out to a depth of at least about 700 mm.

Depth 530 mm (refuse) - Suctions in this layer are generally much higher than the suction in the two layers located on either side. The suction in this layer also takes longer to respond to rain.

Depth 850 mm (refuse) - suction conditions within this layer were persistently low (below about 100 kPa).

Although the profile wets up after rain there is no evidence of a vertically moving 'wetting front'. The suction in one layer may remain high while the suction in the layers above and below drop. This once again suggests that lateral movement of moisture in the refuse is significant, and that small aquifer systems are present in the refuse profile. It should also be noted that water moves within the profile long before field capacity is reached.

This part of the landfill appears to dry out to depth of at least 700 mm, although roots do not extend below a depth of 200 mm . At a depth of 700 mm the moisture content appears not to change. The profile dries out to suctions much lower than wilting point. The drying process also does not proceed from top to bottom, suggesting that water movement during drying may also proceed along lateral pathways.

2.2 Plot 2

The hole on this plot was drilled to a depth of 950 mm. The cover layer was found to be 600 mm deep here, although pockets of plastic were found at depths of about 200 mm and 400 mm. Four psychrometers were located within the cover layer, and two were located in the refuse below.

Depths 50 mm and 230 mm - (cover material) - The psychrometers placed at these depths have very rarely given useable readings. This is due to thermal gradients, which cause errors in the psychrometer output.

Depths 410 mm and 590 mm - (cover material) - The suction in the upper of these two layers is persistently higher than the suction in the lower layer. The suctions change synchronously, dropping about four days after rainfall has occurred, and rising again after five to ten days of dry weather. The suction changes in these two layers may represent wetting and drying fronts which move vertically, since changes appear to take place from the top down. Fronts which move vertically would be expected to occur in the cover layer, since the layering of different types of material is not as pronounced as in the refuse. (There are however, small pockets of plastic between the two psychrometers.)

Depths 770 mm and 950 mm - (refuse) - The suction at the 770 mm level is the highest in the entire profile (apart from the very top layers). The suction in the 950 mm deep layer is the second highest. This pattern again suggests that lateral movement of moisture is occurring in the refuse. The suction in these two layers also changes synchronously, with the suction in the two layers described above. Suctions much higher than wilting point are reached in these two layers during dry weather, although the suction does not go higher than about 3 500 kPa, (the suction above which methanogenic bacteria become dormant.)

The profile wets up at suctions much lower than those corresponding to field capacity, and dries out to depths of at least 1 m, even though no roots are found to penetrate deeper than 200 mm. Although large cracks were present on the surface of plot 2, these had no discernable influence on the speed at which moisture contents within the profile took place.

2.3 Plot 3

The hole on plot 3 was drilled to a depth of about 1100 mm. The cover was found to be about 600 mm thick. Three psychrometers were placed in the cover layer, and another three were placed within the refuse layer.

Depths 50 mm and 250 mm - (cover material) - Once again the psychrometers placed at these depths have very rarely given useable readings. Thermal gradients were again found to be the cause of the problem.

Depth 450 mm - (cover material) - The suction within in this layer was generally the lowest in the profile. It did, however dry out to fairly high suctions during dry spells. The highest suction it dried out to was about 1 500 kPa (wilting point), although no roots were found to extend to this depth. The suction in the layer changes synchronously with the suction in the layers below it.

Depths 650 mm; 850 mm and 1050 mm - (refuse) - The suction in these layers generally increases with depth. Suction changes at the three levels all follow the same pattern, dropping within about four days of rain, and rising again within five to ten days of dry weather. Fluctuations at the 650 mm depth are far greater than at the 850 mm depth and the 1050 mm depth. This layer seems to respond to evaporative gradients and wetting fronts faster than do the other two. This may be due to its closer proximity to the surface, or its moisture conducting properties, or both. Suction conditions at the lowest level are the most stable, although even here large fluctuations in suction are found. Once again, suctions in the refuse layers rise to considerably higher levels than wilting point, and the layers wet up at suctions much higher than that corresponding to field capacity.

2.4 'Control Plot'

The hole on the control plot was drilled to a depth of 600 mm. The cover was found to be 400 mm deep here. Three psychrometers are located within the cover layer, and a fourth is located within the underlying refuse.

Except for the uppermost psychrometer, (which was most often unreadable because of thermal effects,) the suctions within the profile are very low. This site lies in a general depression, in which water may pond. This may explain why it is generally wetter than the other three sites. Although the suctions are low, a trend of drying out during dry spells, and wetting up after rain is detectable. In general, the suction decreases with depth, although the differences between levels is small.

The in-situ suction monitoring has shown that the upper layers of the refuse can dry out to high suctions, to depth of up to at least a metre. Drying occurs despite the fact that no roots extend below 200 mm in the profile. Suctions much higher than wilting point are found at these depths.

Water moves within the profile long before field capacity is reached. Rainfalls as low as about 4 mm in depth affect suctions to depths of up to 750 mm.

There is evidence of lateral moisture movement during wetting up and drying out of the refuse layers. Moisture movement within the cover layer may, however, be vertical. It appears that moisture moves vertically through the cover, and then is intercepted by a layer of refuse (which would slope gently downwar' l to the original working face of the landfill.) The moisture then appears to move alon' -use layers. There is evidence that drying occurs along the same paths.

The suction in deeper parts of the profile takes about four days to respond to rain, and five to ten days to respond to evaporative gradients. It might be expected that wetting and drying of the deeper parts of the profile would be accelerated by the presence of cracks in the cover. No significant difference in the rate of response of suction to rain or evaporative gradients was found between the monitoring hole located near cracks, and those not located near cracks.

CHAPTER 12

PREDICTIONS OF LEACHATE PRODUCTION FOR LINBRO PARK LANDFILL

In this chapter, a number of predictions for leachate production for the test section of Linbro Park landfill are reviewed. Some of the predictions have been made using gross water balances, while others have taken into account the distribution of water within the profile. Balances have been carried out on monthly, weekly, and daily bases. The results of these calculations are discussed below. Short-comings of the predictive methods are also discussed.

1 PREDICTIONS USING SIMPLE WATER BALANCE METHODS

Hojem, 1988, carried out a number of water balance calculations for the profiles of the two auger holes of Linbro Park landfill. He used a gross water balance method, assuming that the profile starts to drain only once field capacity has been reached. Numerous combinations of methods to predict infiltration, and evapotranspiration were used.

He used the SCS method, as well as the rational method to predict runoff, (assuming that the water that did not run off, infiltrated.) He predicted potential evapotranspiration by using 0.7 times average pan evaporation. He also used Thornthwaite's method to predict potential evapotranspiration. To calculate actual evapotranspiration he used Thornthwaite's tables, assuming evaporative zone depths of 200 mm and 1000 mm.

The analyses were carried out using actual rainfall data measured for the site, (for a period of one year,) as well as using mean rainfall figures, and the mean plus one standard deviation of the rainfall. Analyses were carried out on daily, weekly and monthly bases.

In total, 22 different combinations of approaches were used. A number of combinations yielded a nil percolation result, while the highest prediction of percolation was 272 mm (or about 40% of the annual average rainfall) per year. In general, calculations done on a daily basis yielded a higher leachate production than did calculations done on a weekly basis, and weekly calculations yielded a higher result than did monthly calculations.

Assessing all the results together he estimated that the part of the landfill near the North auger hole would start producing leachate in the year 2001. His prediction for the portion of the landfill surrounding the South auger hole is that it would start producing leachate in the year 2003. He estimated the annual leachate production to be 136 mm (or 20 % of the mean annual precipitation) per annum assuming a 1000 mm deep evaporative zone, and 213 mm (or 30% of the mean annual precipitation) per annum assuming a 200 mm deep evaporative zone.

Hojem's calculations are conservative in some aspects, and not in others. As discussed in Chapter 5, the assumption of an evaporative zone of maximum depth 1 m is probably conservative. On the other hand assuming that the profile only starts to drain once it has reached field capacity would tend to underestimate total downward moisture movement (although it should have little effect on the annual figure.) The assumption would overestimate the time which it takes for the landfill to reach more or less steady state conditions. In Hojem's analyses, the field capacity of the landfill profile was taken to be 60% (m_s/m_w). Figures quoted in Chapter 8 suggest that this is a conservative estimation.

The use of daily rainfall for the period 1987-1988 would lead to a conservative result since this was a wet year. (Rainfall was about 140 % of the mean annual figure.) The use of average rainfall figures would tend to under predict percolation through the cover (because they do not allow for the effects of wet spells.) Using the mean plus one standard deviation, however, seems to be unnecessarily conservative.

Hojem neglected interception in his infiltration calculations. This would also lead to a conservative result.

2 PREDICTIONS USING HELP

HELP (Schroeder et al, 1983, and Schroeder, 1989) calculates the water balance on a daily basis and uses actual or synthetically generated values for precipitation.

If HELP's parameters for field capacity and wilting point (quoted in Chapter 8) are used a conservative estimation of leachate production would result. (Measurements made during this project, show HELP's parameters to be conservative). HELP does, however,allow the user to specify his own soil and refuse parameters.

HELP does not use an iterative implicit solution of the generalised flow equations, but uses a solution of Darcy's law, adjusting permeability for moisture content. The profile is allowed to drain to wilting point (as compared to Hojem's assumption that the profile drains to field capacity.) Based on the results of the field tests presented in Chapters 9 and 11, this appears to be a more realistic assumption. The total predicted leachate production would be expected to be higher using this assumption. The simulated landfill profile would also be expected to reach 'steady state' conditions sooner under this assumption.

The depth of the evaporative zone is limited to the depth specified by the user. One would expect that specifying a shallow zone would lead to a conservative result. HELP takes account of the effect of leaf area index on evapotranspiration. A greater percentage of evapotranspiration may therefore be predicted, than by using Thornthwaite's, tables.

On the basis of the findings presented in Chapter 10, the application of the SCS method to assess runoff is expected to be accurate. HELP also takes interception losses into account in predicting infiltration depths.

The HELP model was run to predict leachate generation for the test section of the landfill, based on the profile of the South Auger hole, and the and soil and refuse data quoted in Chapter 8.

Actual daily rainfall data from a nearby weather station (Jan Smuts Airport), with a 30 year record, was used. HELP runs only 20 years of rainfall data at a time. The programme was run firstly for the years 1970 to 1989, using actual data from those years. Since HELP does not contain a synthetic rainfall generator appropriate for the Johannesburg area, the years 1990 to 2020 were simulated by repeating the 30 year rainfall record.*

The programme was run for evaporative zone depths of 200 mm and 1000 mm. The results obtained are summarised in the table below.

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*Statistically, this is a reasonable practice, since a thirty year record is long enough to contain data representing drought years and wet years.

Dates	Element Predicted	Prediction for 0.2 m Deep Evaporative Zone *	Prediction for 1 m Deep Evaporative Zone *
1970 to 1989	•Average Runoff	1.3 %	0.4 %
	•Average Evapotranspiration	75 %	60 %
	•Average Leachate Production	0.01 %	0.01 %
	•Average Change in Moisture Storage	23 %	40 %
	•Maximum Daily Rainfall	26 %	26 %
	•Maximum Runoff	16 %	5 %
1990 to 2009	•Average Runoff	1.2 %	0.4 %
	•Average Evapotranspiration	80 %	80 %
	•Average Leachate Production	0.01 %	0.01 %
	•Average Change in Moisture Storage	19 %	19 %
	•Maximum Daily Rainfall	26 %	26 %
	•Maximum Runoff	16 %	6 %
2009 to 2020	•Average Runoff	0.4 %	0.1 %
	•Average Evapotranspiration	75 %	74 %
	•Average Leachate Production	0.01 %	0.01 %
	•Average Change in Moisture Storage	24 %	25 %
	•Maximum Daily Rainfall	15 %	15 %
	•Maximum Runoff	2.5 %	1 %

* Figures are quoted as a percentage of the mean annual rainfall

Table 12.1
Summary of Results of HELP Water Balance Calculations

HELP predicts a very much lower annual leachate production (0.01% of the mean annual precipitation) than was predicted by Hojem. HELP's predictions appear to agree with field conditions better than do Hojem's predictions. The average runoff predicted by HELP is very low. This is in line with the results of the sprinkler infiltrometer tests (presented in Chapter 10.) The main difference between the two sets of calculations appears to be that HELP's predictions of evapotranspiration are much larger than Hojem's predictions based on Thornthwaite's tables.

Surprisingly, increasing the evaporative zone depth, actually tended to decrease the predicted percentage of evapotranspiration. This may be linked to assumptions about root distributions (and associated assumptions about partitioning evapotranspirative losses) within the profile.

Assuming a shallower evaporative zone depth also increased predicted runoff. This is what one would intuitively expect. A shallower zone of evaporation would be expected to lead to higher antecedent moisture conditions in general. This would in turn be expected give rise to a greater volume of runoff. The prediction of greater runoff, together with a greater percentage of evapotranspiration is however surprising. If predictions of evaporative losses were found to increase, the simulated antecedent moisture conditions of the surface should be generally lower, and simulated infiltration should therefore increase.In any event the assumption of different evaporative zone depths did not make any difference to the predicted leachate production.

Although HELP's predictions appear to agree fairly well with conditions observed in the field, HELP has the short-coming that it does not take lateral flow into account. Lateral flow in landfills has been shown (in Chapters 9, 11, and 13) to be important. HELP's methods of predicting evapotranspiration also appear (on the basis of data presented in Chapters 9 and 11) to be inadequate. HELP is however easy to run, and has modest data requirements. It may therefore be regarded as a useful tool for the assessment of water balances.

3 PREDICTIONS USING UNSAT-H

Ideally the UNSAT-H programme (Fayer and Jones, 1990) should be run to compare the predictions of leachate production. Hardware-software interfacing problems, together with the difficulty of obtaining software written by United States government departments, under the boycott against South Africa have precluded the possibility of this for this study.

One would expect the evaporative component predicted by UNSAT-H to be higher than that predicted by HELP, and more accurate, (since UNSAT-H does not limit the evaporative zone depth, and takes vapour flow and non-isothermal flow into account.) The infiltration predictions in this programme rely on solution of the Richard's equations. This may not necessarily lead to a greater degree of accuracy, than is achieved by SCS predictions. UNSAT-H also does not allow for lateral flow. Evidence that lateral flow is significant in landfills is presented in Chapters 9, 11 and 13.

4 SHORT-COMINGS IN EXISTING PREDICTION METHODS

The major short-coming of many of the readily available predictive computer programmes for computing water balances appears to be their assumption of one-dimensional flow. A number of computer programmes that model moisture flow in porous media in two dimensions, using a two dimensional form of Richard's equation exist. (eg Yen and Akan, 1983, and Davis and Neuman, 1983) These programmes would be able to take account of anisotropic properties of the porous medium. It would be interesting to apply these programmes to landfills and compare their predictions to the observed field conditions.

Another difficulty encountered in calculating leachate production is that relationships between moisture content, suction, and hydraulic conductivity for refuse appear to be ill-defined.

Surprisingly, ignoring the presence of large cracks in the surfaces of landfills appears to have little effect on runoff predictions, (for light to moderate rainfall) based on the SCS method. If the data measured in the field tests using the double ring infiltrometers were to be used in the Kostiakov, the Holtan, or Horton's equation to predict infiltration, the effect of the cracks would be significant. These predictions would probably only be valid for heavy rainfall, where ponding could occur. It would be of interest to ascertain whether ignoring the presence of cracks would affect infiltration predictions based on Richard's equation.

CHAPTER 13

CONTAMINANT MIGRATION AT COASTAL PARK LANDFILL

This chapter describes the results of studies carried out on the migration of contaminants at a landfill situated in the Cape Province.

The landfill, known as Coastal Park landfill is run by the Cape Town City Council. The landfill is situated on the Cape Flats near Muizenberg. It is underlain by Cape Flats Sand and has an unsaturated zone that is two metres thick. The refuse is placed and compacted in cells that are 5 m high. The intermediate and final cover is sand. Deposition of refuse was started in 1986 and the intended life of the site is 20 years.

This landfill is, (like Linbro Park landfill,) situated in an area of annual water deficit. (The annual potential evapotranspiration exceeds the annual rainfall) It does however have a seasonal water surplus, during winter, when the potential evapotranspiration is low. Winter is also the rainy season at this site. The landfill is not underlined and emits leachate during the winter months. Landfill gas is not presently extracted, but an experimental well field is currently being installed.

Two different series of tests were performed at his site. The first involved sampling a number of holes dug in the landfill itself, to a depth of about 6m. The aim of these tests was to monitor migration of contaminants within the landfill itself.

The second test series involved sampling a line, starting at the toe of the landfill, and extending some 10 m away from the fill. The aim of this set of tests was to try and monitor lateral movement of contaminants within the unsaturated zone of the toe of the landfill.

Samples recovered during this exercise were analysed by preparing extracts from the samples, (in the manner described in Appendix B.) The extracts were then analysed chemically for pH; chemical oxygen demand (COD); total dissolved solids; conductivity; alkalinity; ammonia;

chloride; sodium; and potassium. In addition, moisture contents, field capacities, and suctions of some of the samples were tested. These tests were carried out as described in Appendices A, C, and D respectively.

The results of the two series of tests are described below.

1 CONTAMINANTS IN THE LANDFILL PROFILE

Four holes were sampled in this test series. The first hole was sampled twice, at the end of the dry season (May) and at the end of the wet season, (October) in 1988. The samples from this hole were tested by Hojem (1988). The other three test holes, spaced about 20 m apart, to roughly form a triangle, were sampled at the end of the dry season in 1990. The samples from these three holes (alpha, beta, and gamma) were analysed as part of this project.

The aim of sampling three holes, spatially separated is to gain an idea of whether it is valid to use results from one test hole as a basis on which to predict the behaviour of the whole landfill, or whether holes some distance from one another, differ radically. The results of the 1988 tests and the 1990 tests are shown in figures 13.1 (a) to (j), and are discussed and compared below.

1.1 Moisture Content

(See figure 13.1 (a)) The results of the 1988 tests show that the entire profile wets up during the wet season. Although field capacity for this hole was not measured, based on the figures obtained for field capacity for the other three holes, the moisture content of the profile, even at the end [illegible] season is below field capacity. This demonstrates, (as pointed out in chapter [illegible] moisture moves within the profile at moisture contents considerably lower than field capacity.

The moisture contents of the four holes at the end of the dry season is fairly similar, except for one point in hole alpha at a depth of 5m. The values of field capacity measured showed holes alpha, beta and gamma to be well below field capacity at the end of the dry season.

A rough calculation of the velocity of water within the profile, assuming one dimensional vertical flow, and based on changes of average moisture content between the wet season and dry season yields a velocity of about 1 m per year. (3×10^{-6} cm/s)

1.2 pH

(See figure 13.1 (b)) The hole sampled in 1988 showed a decrease in pH during the wet season. This is unusual since increased moisture contents usually favour methanogenic conditions, and pH levels drop under these conditions. The decrease in pH may, however be related to the greater concentration of contaminants in the profile during the wet season. The pH in all three holes is similar, being equal to about 8. This indicates that methanogenic conditions prevail within the site. The COD within the profile, is therefore expected to be low.

1.3 Chemical Oxygen Demand

(See figure 13.1 (c)) The COD levels within the holes are generally low, and are typical of methanogenic conditions, (as expected judging by the pH levels.) There is one zone (at a depth of about 4 m) in the hole tested in 1988 which has an extremely high COD. This zone corresponds to high moisture contents, and high concentrations of other contaminants. This suggests that a pocket of pollutants has been washed to this part of the profile during a wet spell.

1.4 Total Dissolved Solids

(See figure 13.1 (d)) The TDS levels within the four holes shows a degree of variation. The variation is generally within a factor of two, however. Peak concentrations of pollutants similar to (although not as marked as) the one found in 1988, show up in holes alpha, beta, and gamma, at levels of 4.5 m to 6 m. The fact that these concentrations are found at similar levels, indicates that pollutants may have been transported to this part of the profile by similar mechanisms. In many of the chemical analyses, hole beta shows a peak concentration of pollutants at a level of 1.5 m also.

The concentration of salts within the hole sampled in 1988, increased during the wet season. This shows that salts are being transported to this part of the profile during the wet season. Since the concentration of salts higher up in the profile has not changed significantly, the salts have evidently not washed in from above. This observation yields more evidence that lateral movement within landfills is dominant.

The peak in concentration of salts in the hole sampled in 1988, at the 4 m level, increased with respect to the mass of dry solids during the wet season. The concentration of salts in the water held by the refuse has, however, not changed.

It should also be noted that in the analyses carried out in 1988, the concentration of salts in the upper layers is higher at the end of the dry season, than at the end of the wet season, indicating upward movement of moisture under evaporative gradients. The concentration of salts at the top of the three holes sampled in 1990 corresponded with levels found at the end of the dry season in 1988, indicating that there has been no net downward migration of salts at the top of the profile.

1.5 Conductivity

(See Figure 13.1 (e)) The trends displayed in the conductivity analysis are very similar to those displayed in the TDS analysis.

1.6 Alkalinity

(See figure 13.1 (f)) The trends displayed with respect to alkalinity levels are very similar to trends displayed in the TDS profile. The alkalinity of the holes is generally more uniform though. This is probably due to the high alkalinity of the cover material.

1.7 Ammonia

(See figure 13.1 (g)) Ammonia contents in the three holes sampled in 1990 are low, except for one result at the 4 m level in hole alpha. Interestingly, this peak does not correspond to peak concentrations of any other contaminants analysed for.

Ammonia levels found in the hole sampl in 1988 were much higher, especially at the 4 m level (corresponding to peak concentrations of other pollutants.)

1.8 Chloride

(See figure 13.1 (h)) Chloride concentrations generally display trends similar to the TDS concentrations. At the end of the dry season in 1988, however, the peak concentration at the 4 m level was not evident. By the end of the wet season it had become prominent. The result again indicates lateral moisture movement within the profile.

1.9 Sodium

(See figure 13.1 (i)) Sodium levels in the three holes sampled in 1990 show much the same trend in concentrations as do the other salts. The levels within holes alpha and beta are, however somewhat higher than those in the hole sampled in 1988, and hole gamma.

1.10 Potassium

(See figure 13.1 (j)) The results of the analysis of the distribution of potassium is very similar to that for sodium.

In general the properties of the material within the four profiles shows a degree of scatter, (as would be expected from a heterogeneous body such ad a landfill.) Similar trends are identifiable, and variations of properties are generally within a factor of two. The degree of scatter is thus not so large that data from one hole cannot be used to predict behaviour of other parts of the landfill.

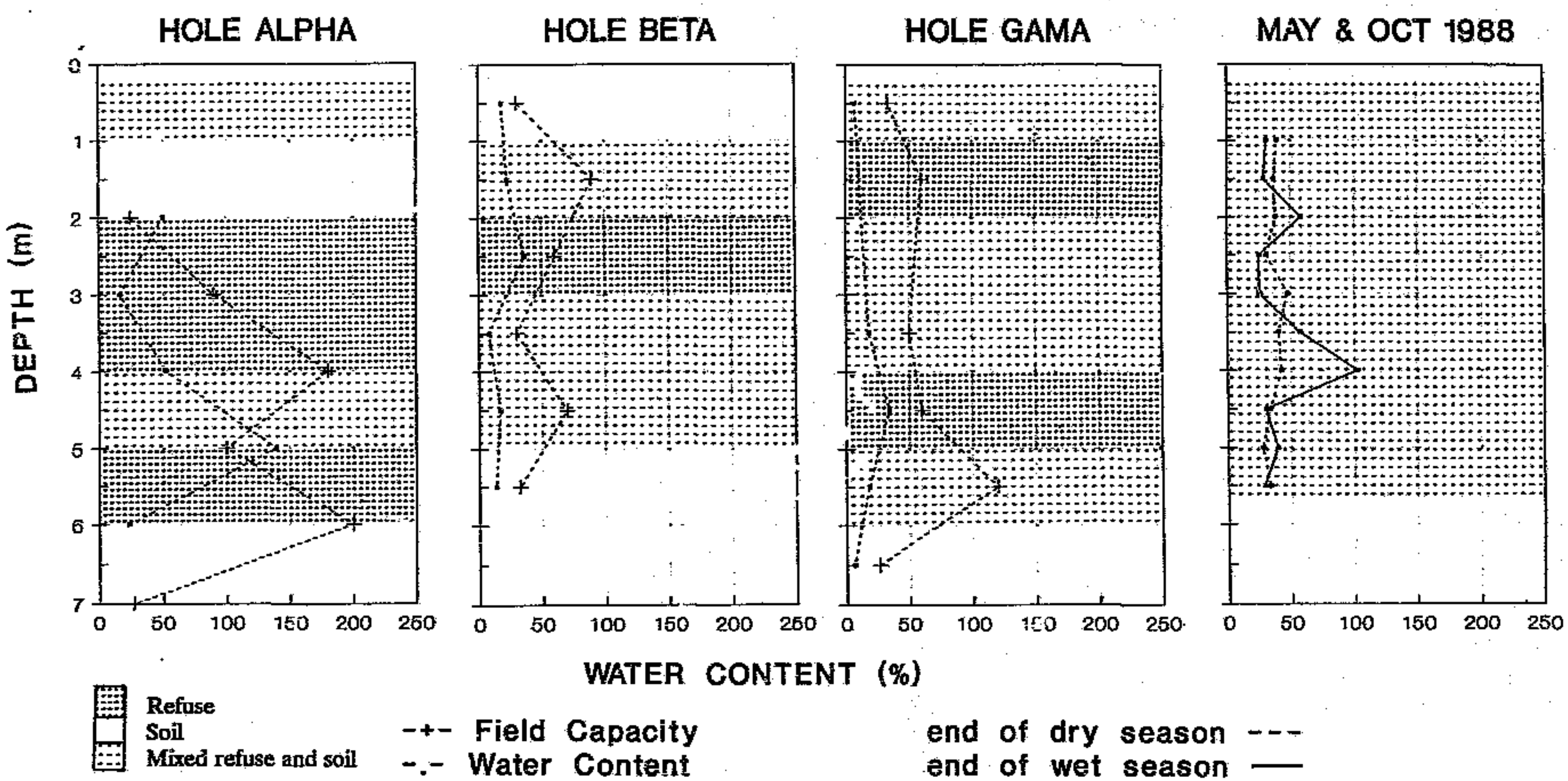


Figure 13.1 (a)
Coastal Park
Water Contents and Field Capacities (m_w/m_s)

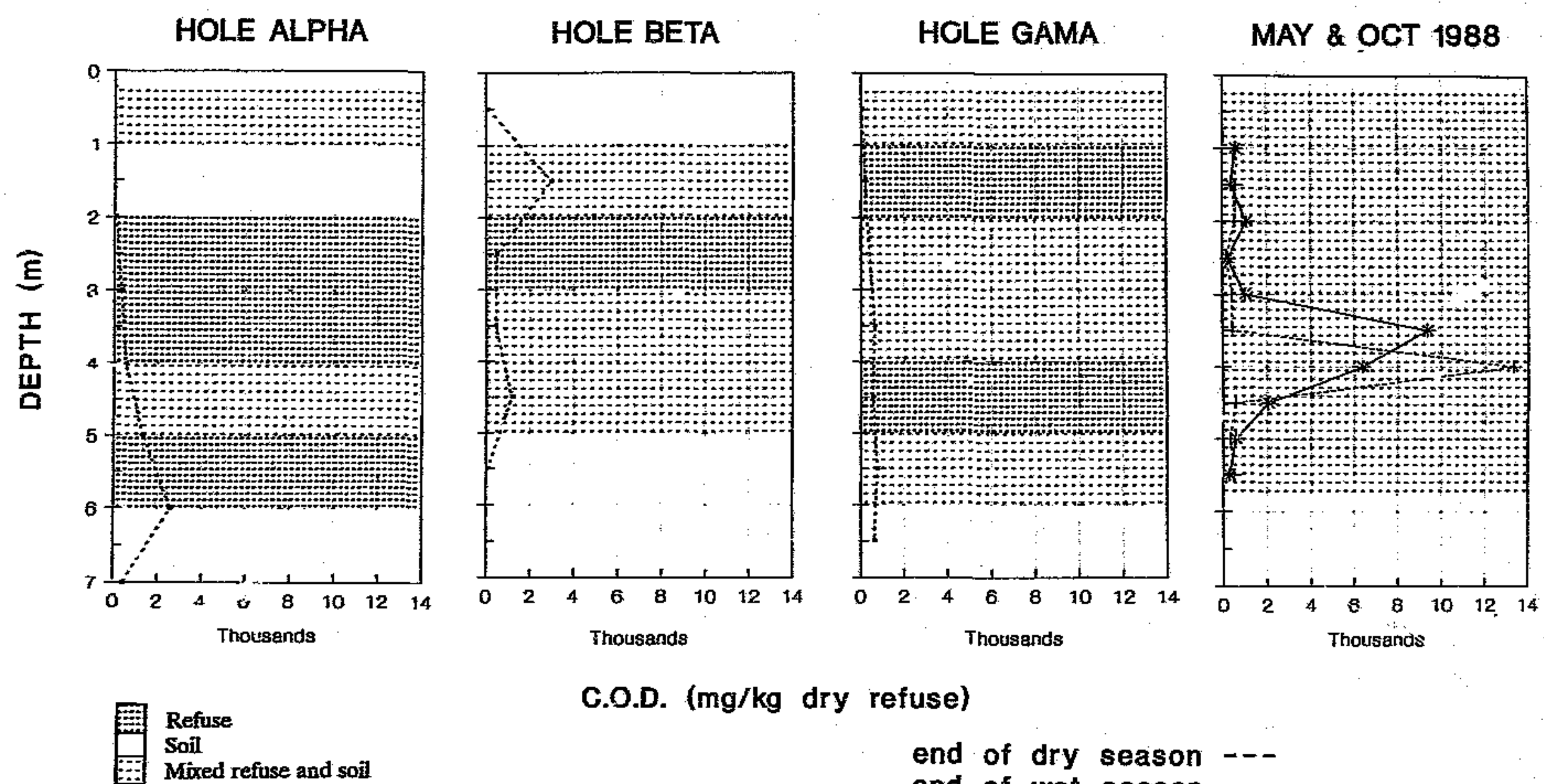


Figure 13.1 (c)
Coastal Park
Chemical Oxygen Demand

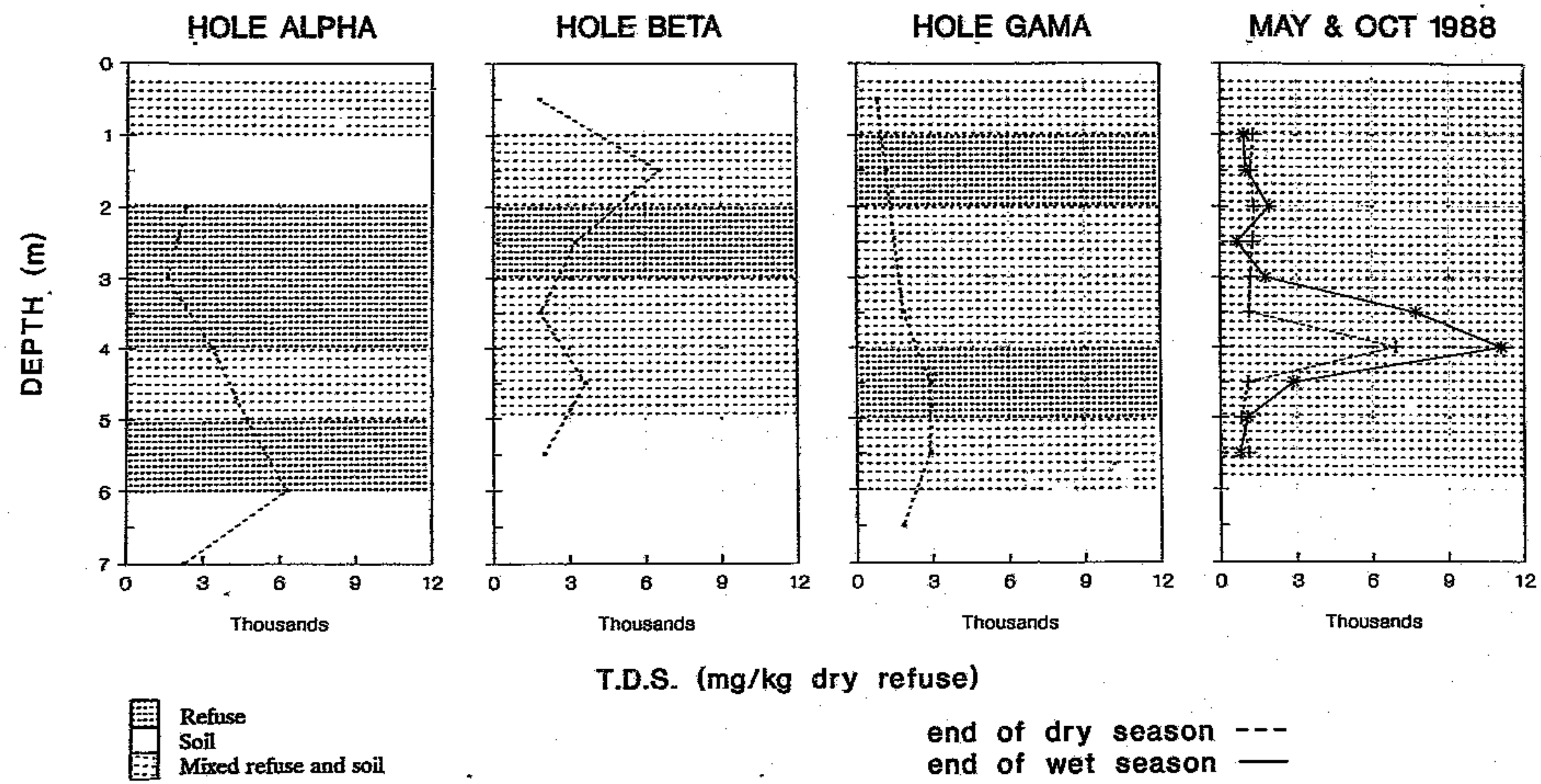


Figure 13.1 (d)
Coastal Park
Total Dissolved Solids Content

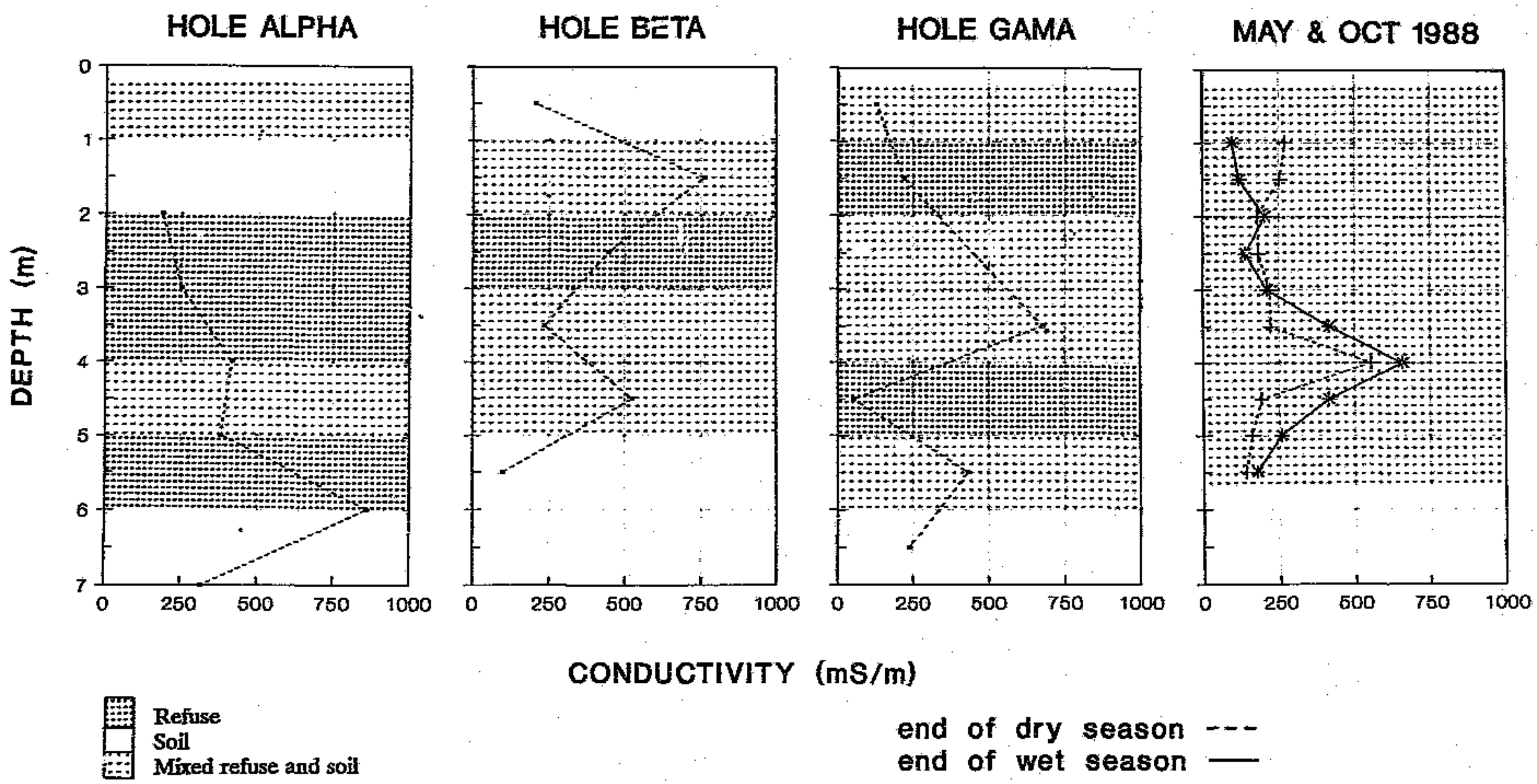


Figure 13.1 (e)
Coastal Park
Conductivity

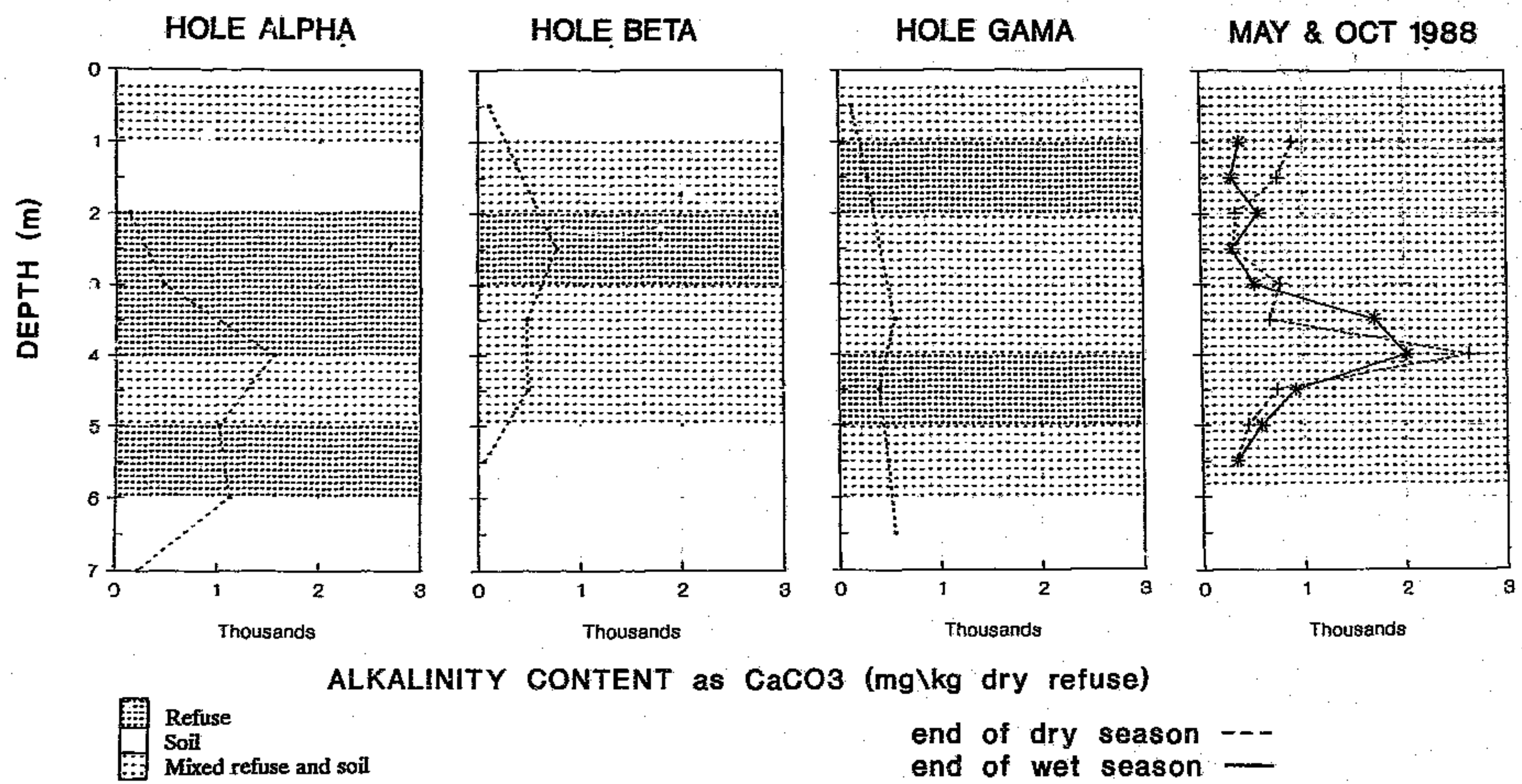


Figure 13.1 (f)
Coastal Park
Alkalinity

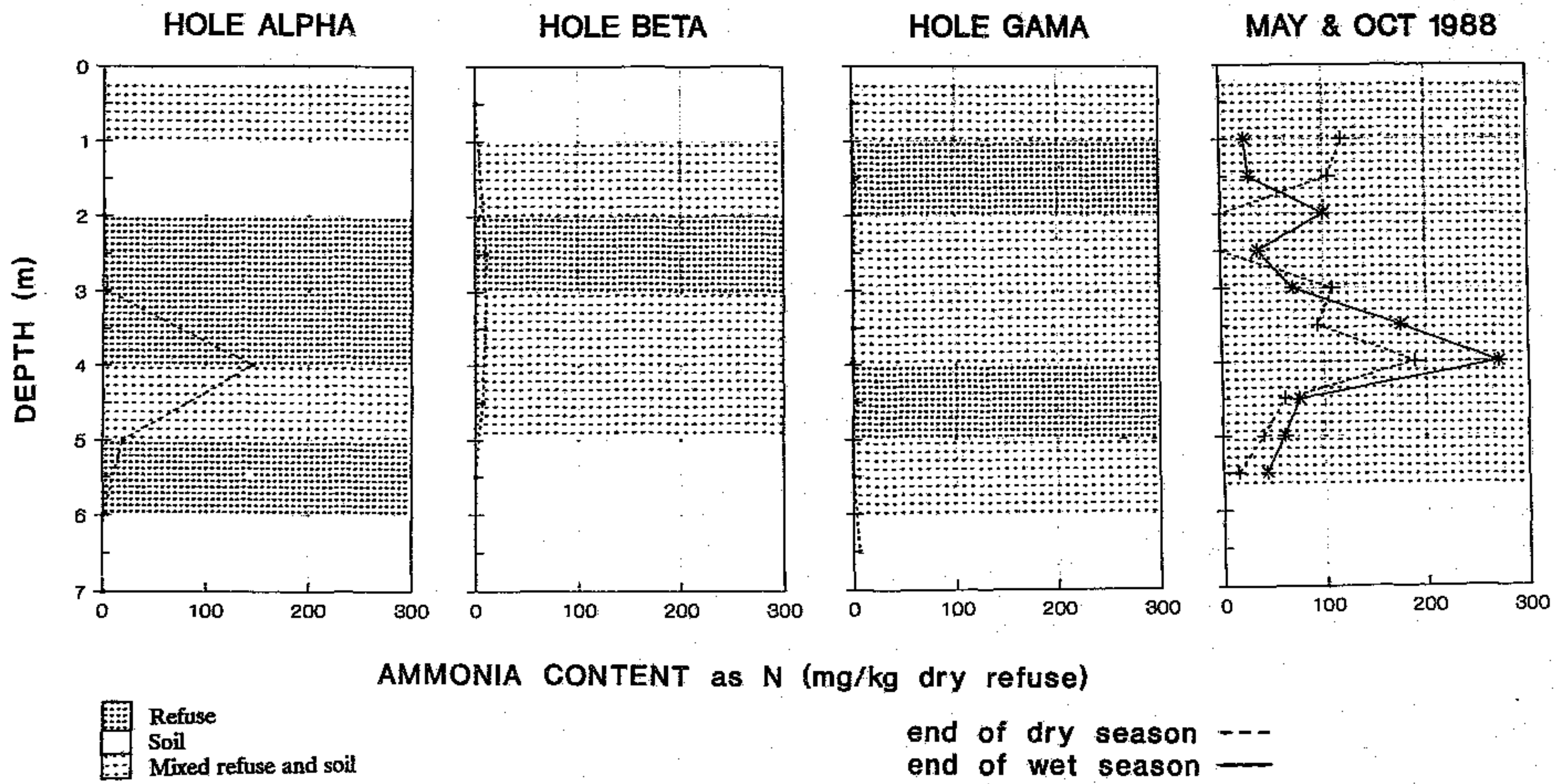


Figure 13.1 (g)
Coastal Park
Ammonia Contents

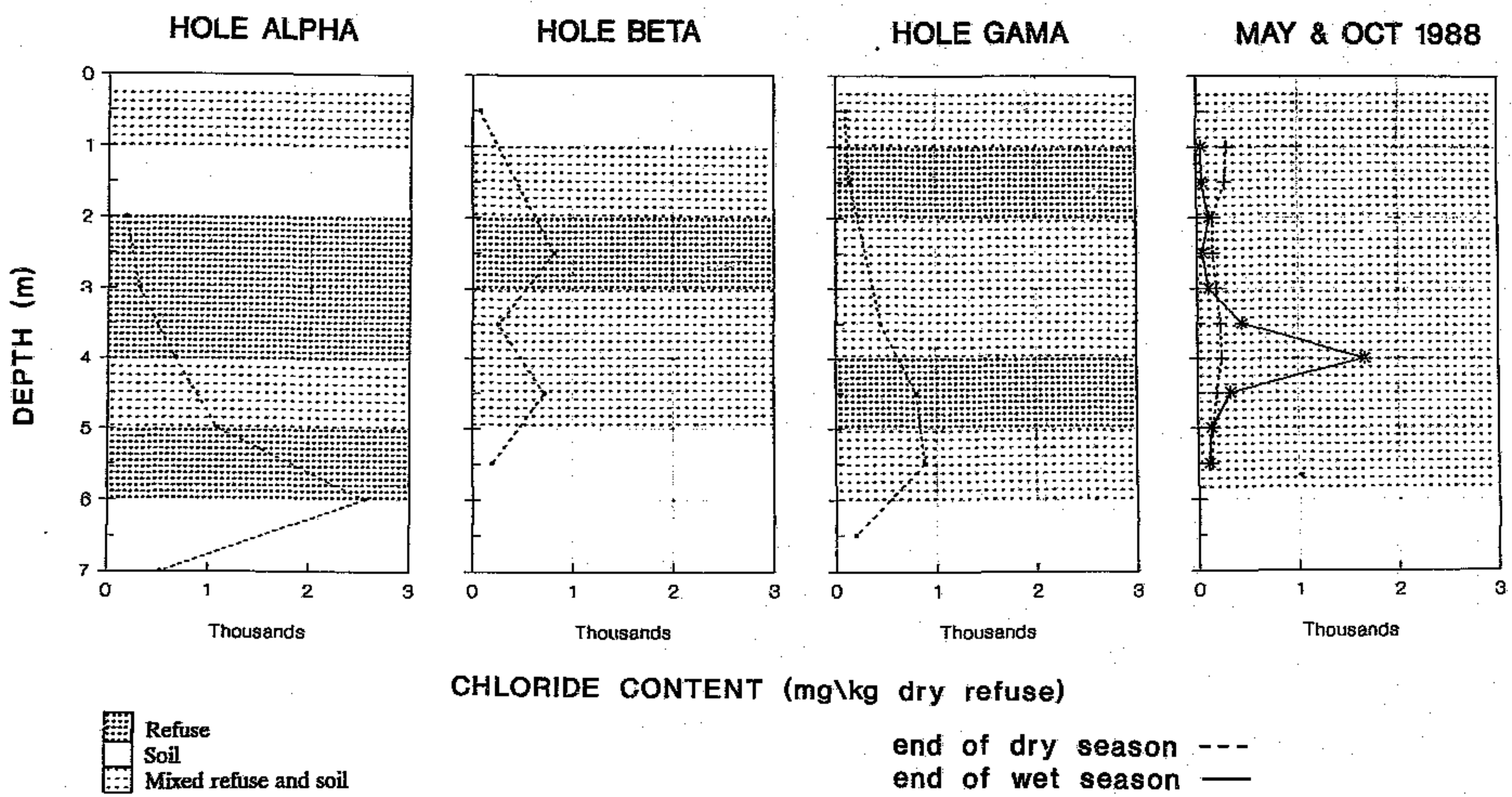


Figure 13.1 (h)
Coastal Park
Chloride Contents

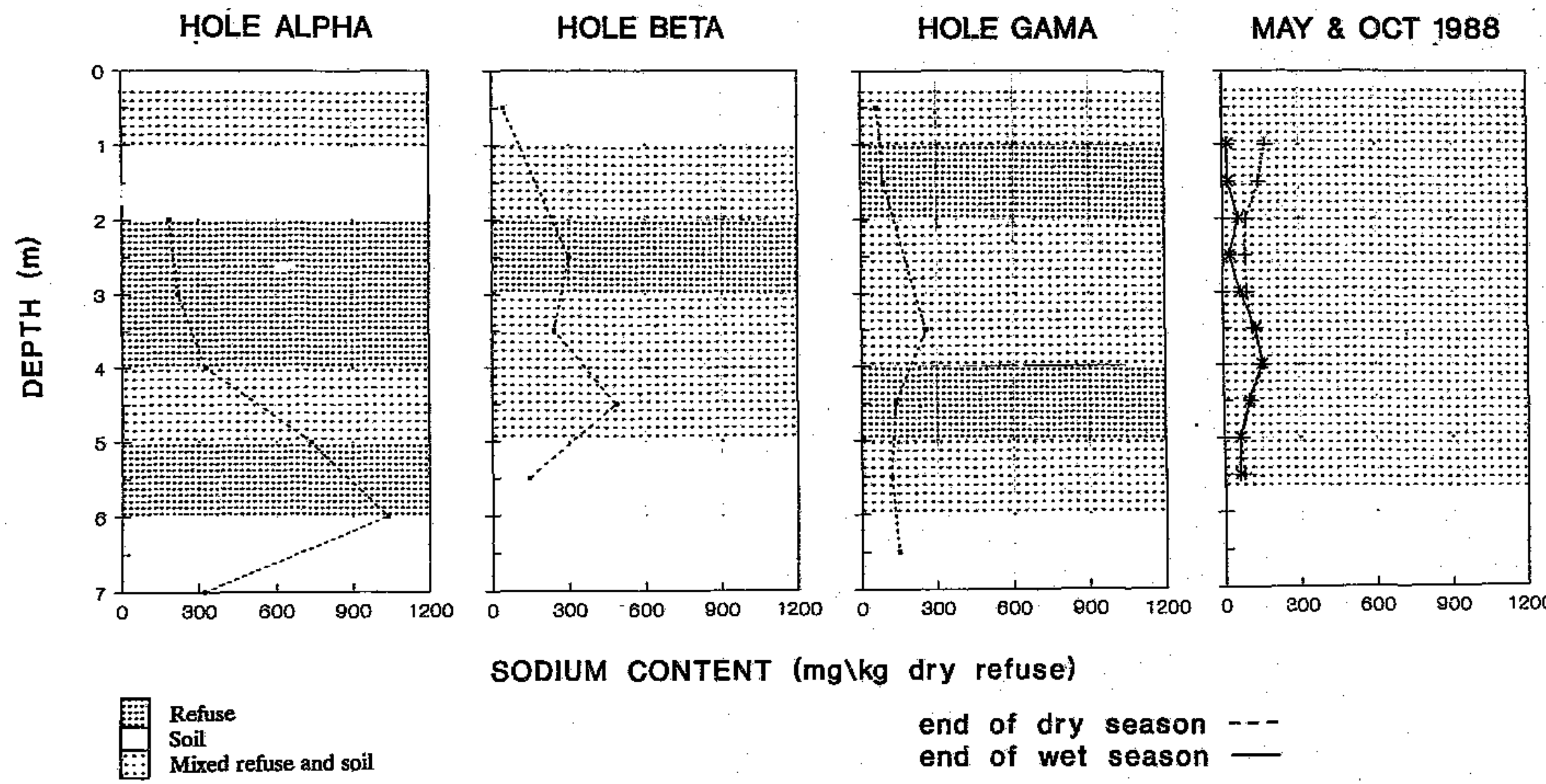


Figure 13.1 (i)
Coastal Park
Sodium Contents

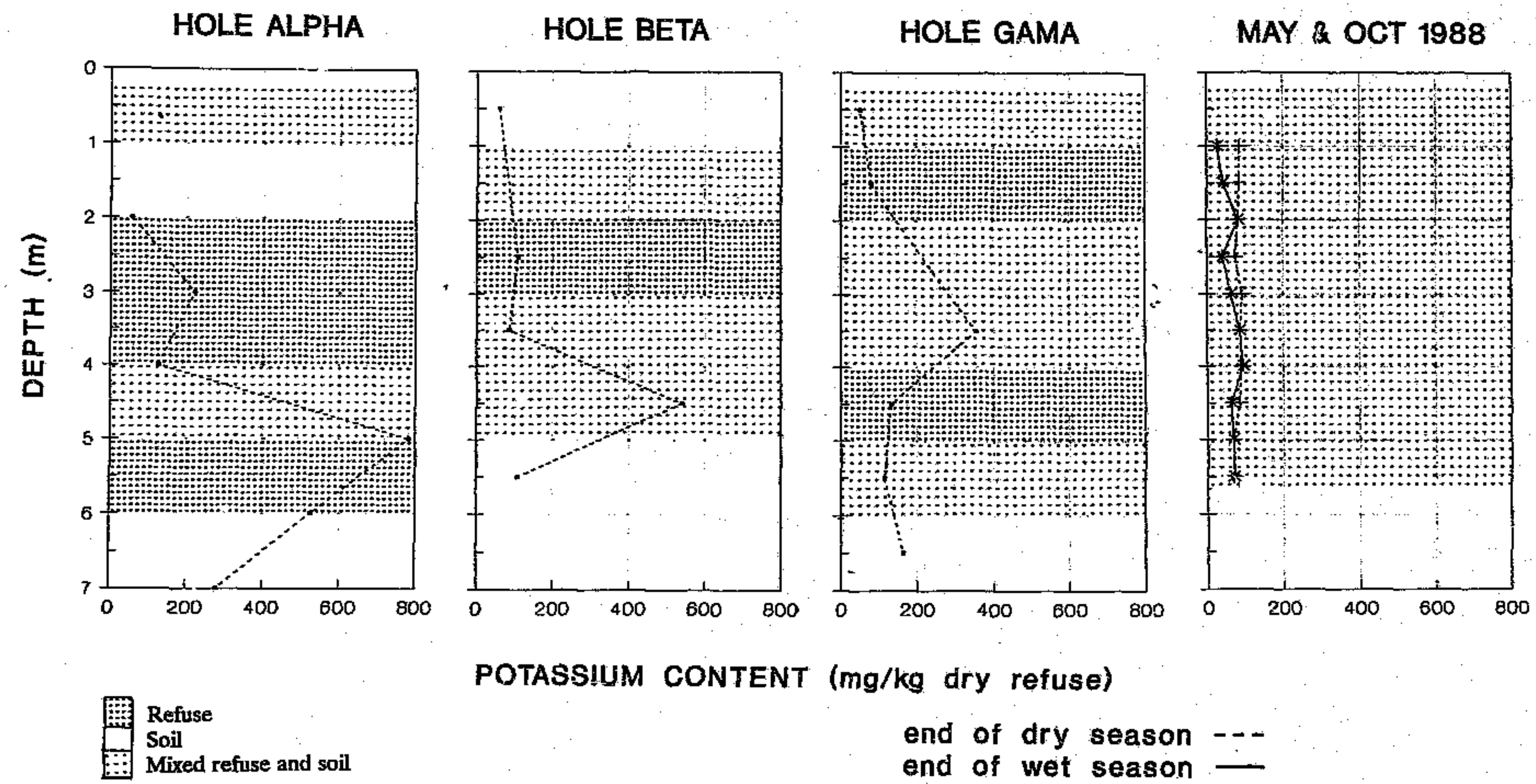


Figure 13.1 (j)
Coastal Park
Potassium Contents

2 CONTAMINANTS IN THE UNSATURATED ZONE

In this set of tests, samples were taken along a line starting at the toe of the landfill, and extending some 10 m away from the fill. Samples were taken at 1 m spacings (in the lateral direction,) and to a depth of 2 m (at 0.5m intervals.) The aim of this set of tests was to try and monitor lateral movement of contaminants within the unsaturated zone of the toe of the landfill.

The samples taken were subjected to chemical analysis, as well as tests for moisture content, and suction. The results of the tests are shown in figures 13.2 (a) to (k) and are discussed below.

In examining the graphical depictions of the test results, it should be noted that depth below surface, (rather than absolute level) has been plotted. The land slopes away from the toe of the fill, towards the sea. The water table occurs at a depth of about 2 m in this zone. The groundwater is saline due to the proximity of the sea.

2.1 Water Contents

(See figure 13.2 (a)) The moisture contents within the unsaturated zone are fairly uniform to a depth of 1 m. They increase at a depth of 1.5 m, and reach saturation at a depth of 2 m. Only those samples at 2 m are above field capacity.#

2.2 Suctions

(See figure 13.2 (b)) The suctions within the unsaturated zone are very small. At the 2 m level, where the saline groundwater is encountered, the suction increases considerably. This increase in suction is due to the increase in the osmotic component of the suction.

2.3 Total Dissolved Solids

(See figure 13.2 (c)) The contours for TDS show high levels at a depth of 2 m. This is to be expected, since this zone lies within the saline ground water. An area of low concentration of salts is evident in the area between 0 m and 2 m from the toe, to a depth of about 0.5 m. A zone of high concentration occurs at the surface at a distance between 3 m and 7 m from the toe. Another small zone of very high concentration is located 8 m to 9 m from the toe, at a depth of 1.5 m.

The field capacity of the sand was found to be about 20% (m_w/m_s)

2.4 Chloride; Sodium; Potassium; Ammonia; Sulphates; Conductivity; and Chemical Oxygen Demand

(See figures 13.2 (d); (e); (f); (g); (h); (j); (k)) The distributions of other contaminants show very similar patterns to the distribution of TDS. In the case of chlorides, sodium and potassium, however, the zone of very high concentration at a depth of 1.5 m (and 8 m from the toe) is not marked. The presence of these substances is probably due to the naturally saline character of the groundwater. High concentrations of sulphates, compounds of nitrogen**, and COD are, however, found here. This suggests that a 'cell' of pollutants has perhaps been released by the landfill. It may perhaps have been released when conditions within the landfill were acetogenic. Conditions appear to be methanogenic now which may explain why a plume of pollution extending towards the landfill is not evident.

The localised high spot of concentrations near the surface suggests that material may be washing through the sides of the landfill or down the slope, contributing to the slightly higher concentrations at this point.

In the case of COD there is an anomaly. The spot where, in the case of other contaminants, low concentrations are found (at 0 m to 2 m from the toe, and 0.5m deep,) a high concentration of COD is found. No explanation for this anomaly has been found.

The results of these tests have indeed yielded information about contaminant distributions within the unsaturated zone. In order to study migration of the contaminants, however, the sampling exercise will have to be repeated at a later date.

Although this chapter does not relate directly to the role of covers in the water balance, it adds to evidence about the nature of moisture movement within landfills and the underlying unsaturated zone. It also demonstrates the degree of similarity in different parts of a landfill and the validity of using fairly isolated samples in the prediction of landfill behaviour.

** It is not clear whether the nitrogen compounds found in the sample originally occurred as ammonia, nitrite, or nitrate. Due to delays in transport, some time elapsed between recovery and analysis of samples, during which time ammonia and nitrites, may have been oxidised to form nitrates.

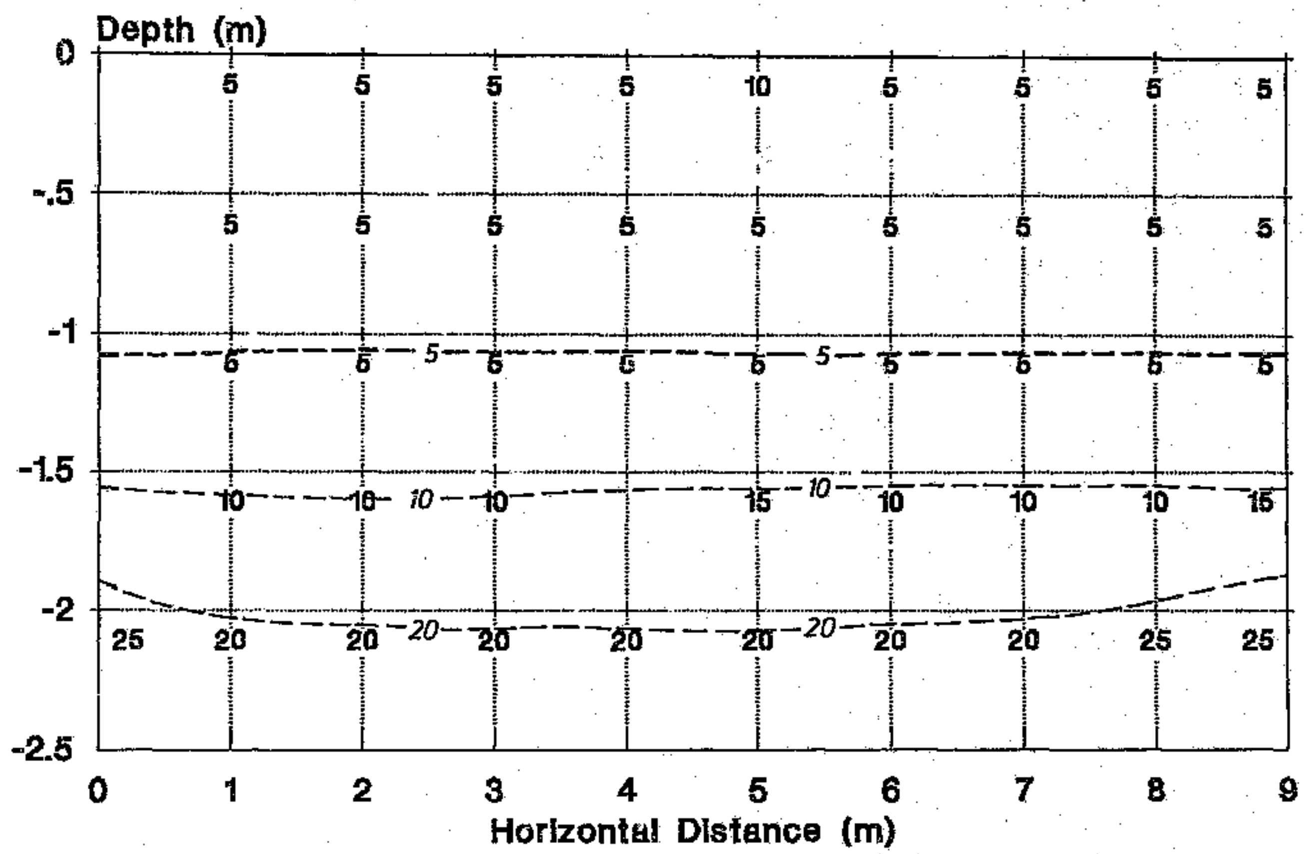


Figure 13.2 (a)
Coastal Park
Water Contents (m_s/m_w) within the Unsaturated Zone

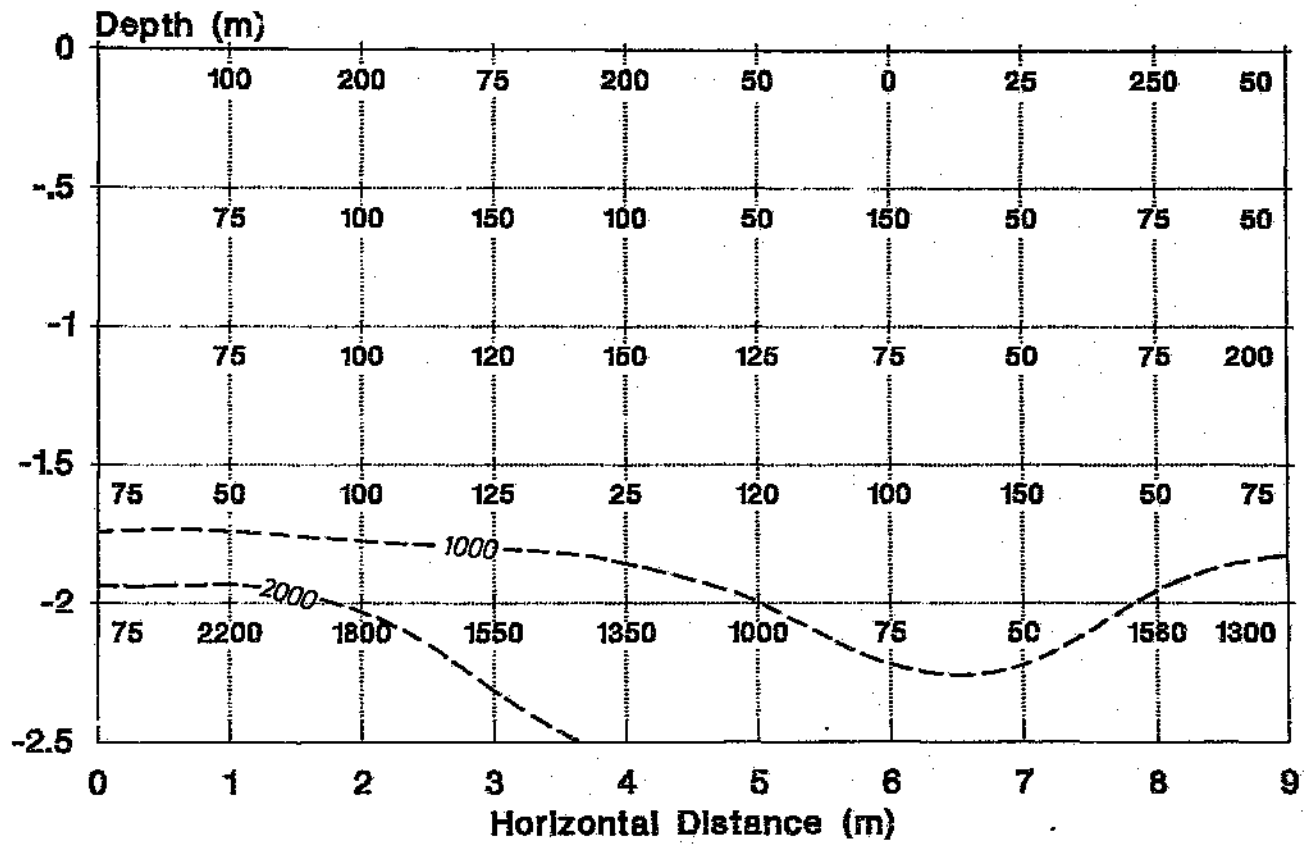


Figure 13.2 (b)
Coastal Park
Suction (kPa) within the Unsaturated Zone

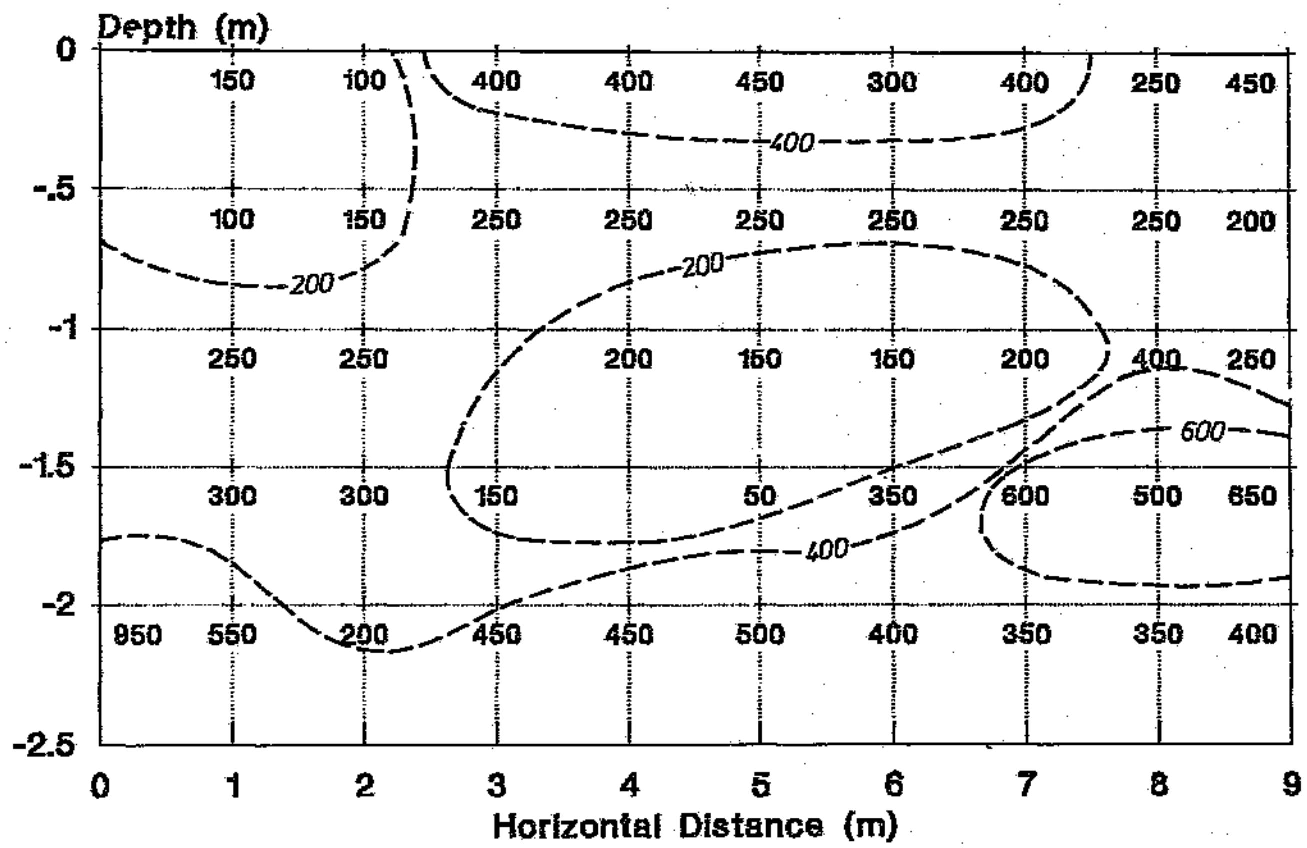


Figure 13.2 (c)
Coastal Park
Total Dissolved Solids (mg/kg dry solids) within the Unsaturated Zone

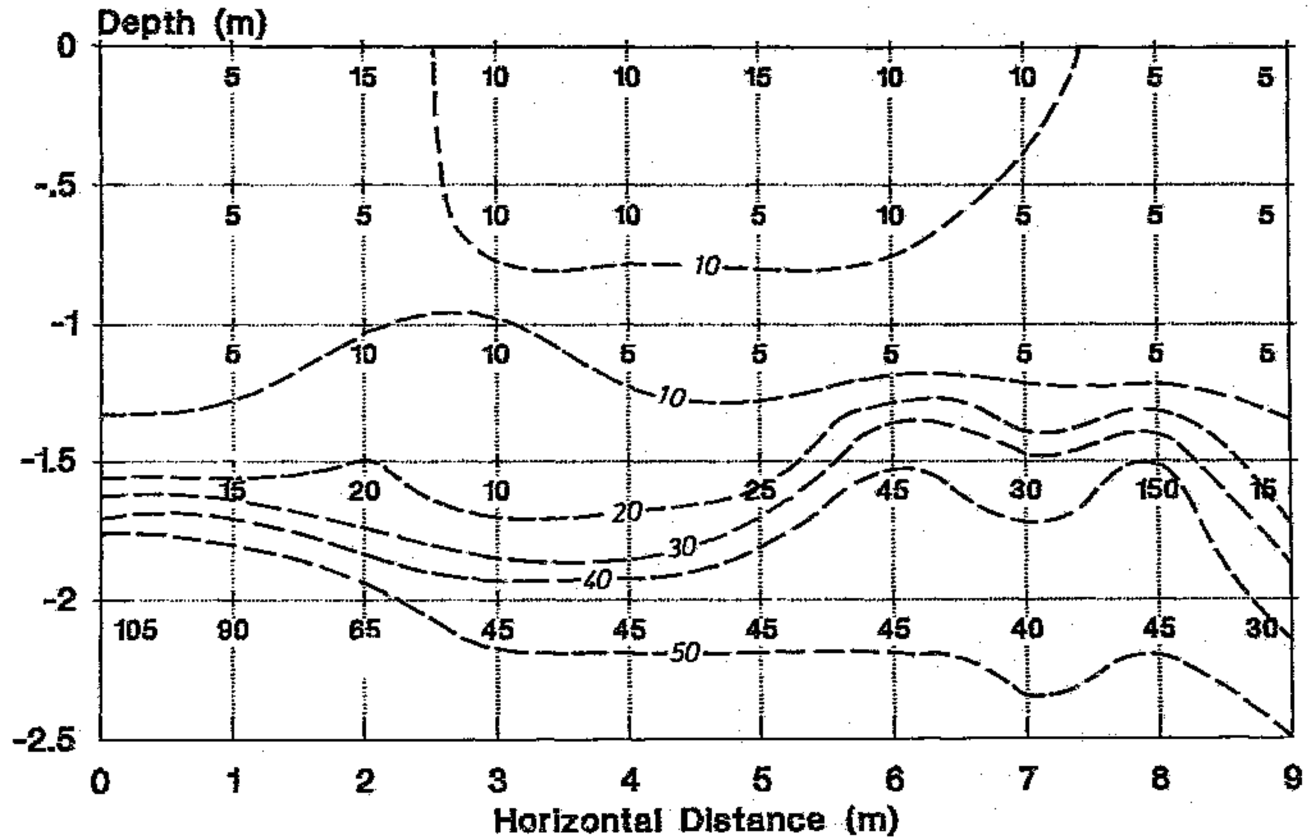


Figure 13.2 (d)
Coastal Park
Chlorides (as Cl, mg/kg dry solids) within the Unsaturated Zone

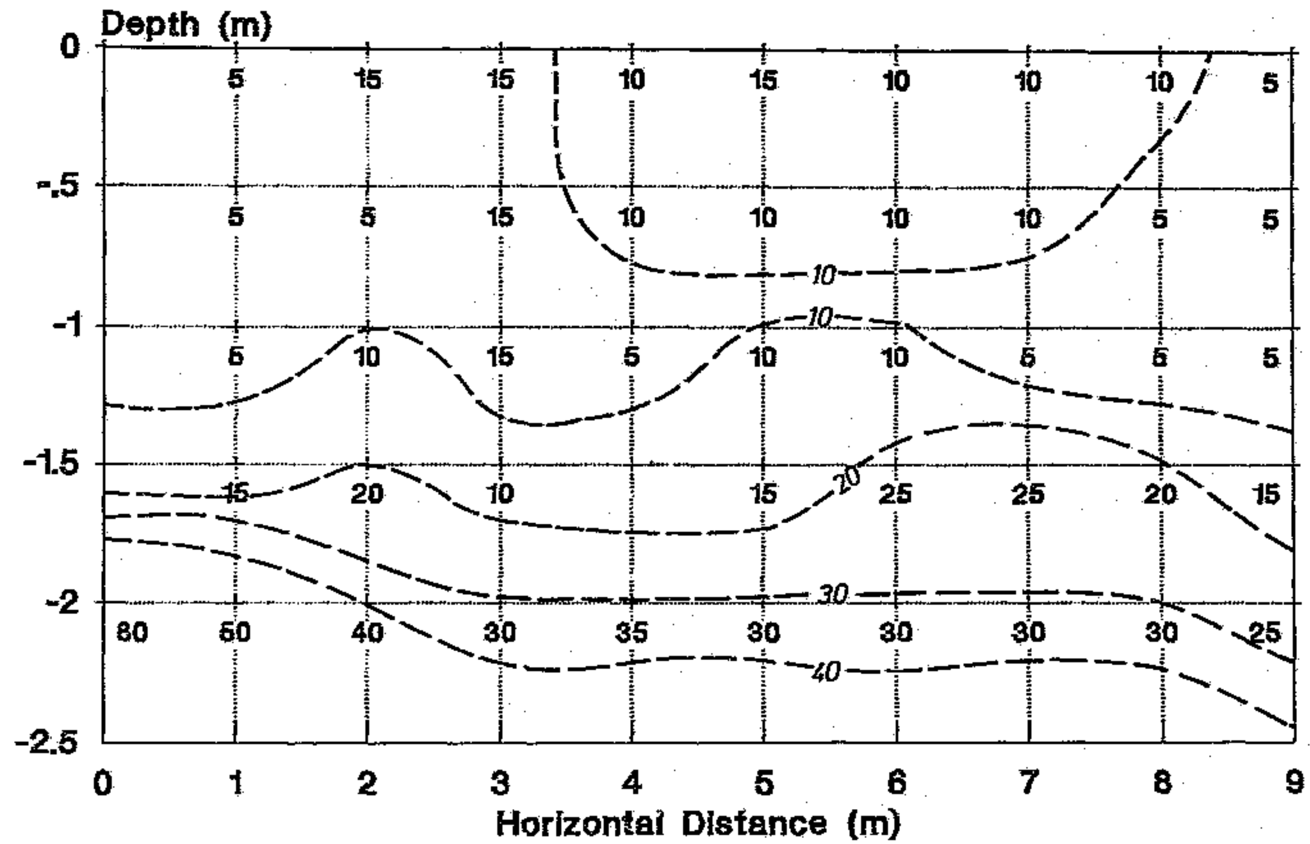


Figure 13.2 (e)
Coastal Park
Sodium (as Na, mg/kg dry solids) within the Unsaturated Zone

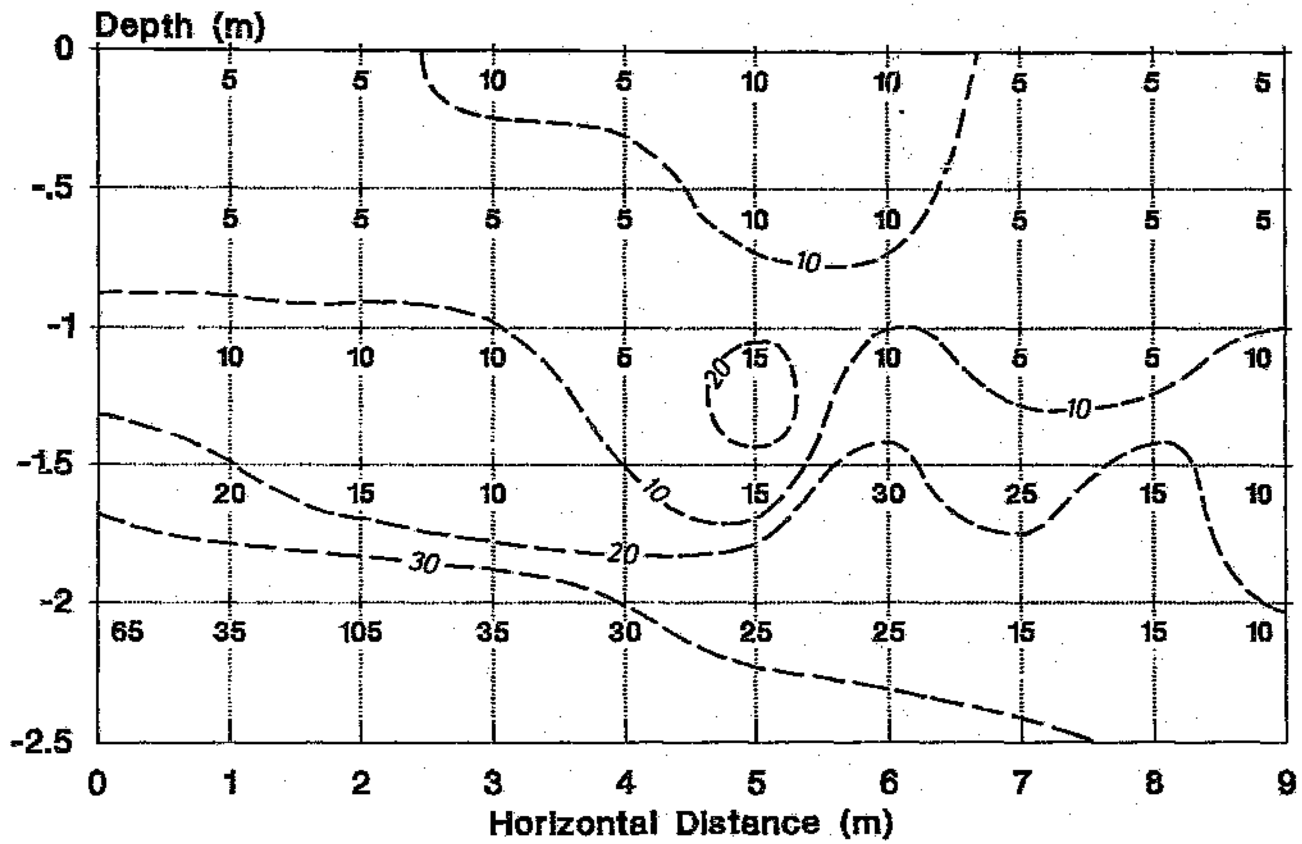


Figure 13.2 (f)
Coastal Park
Potassium (as K, mg/kg dry solids) within the Unsaturated Zone

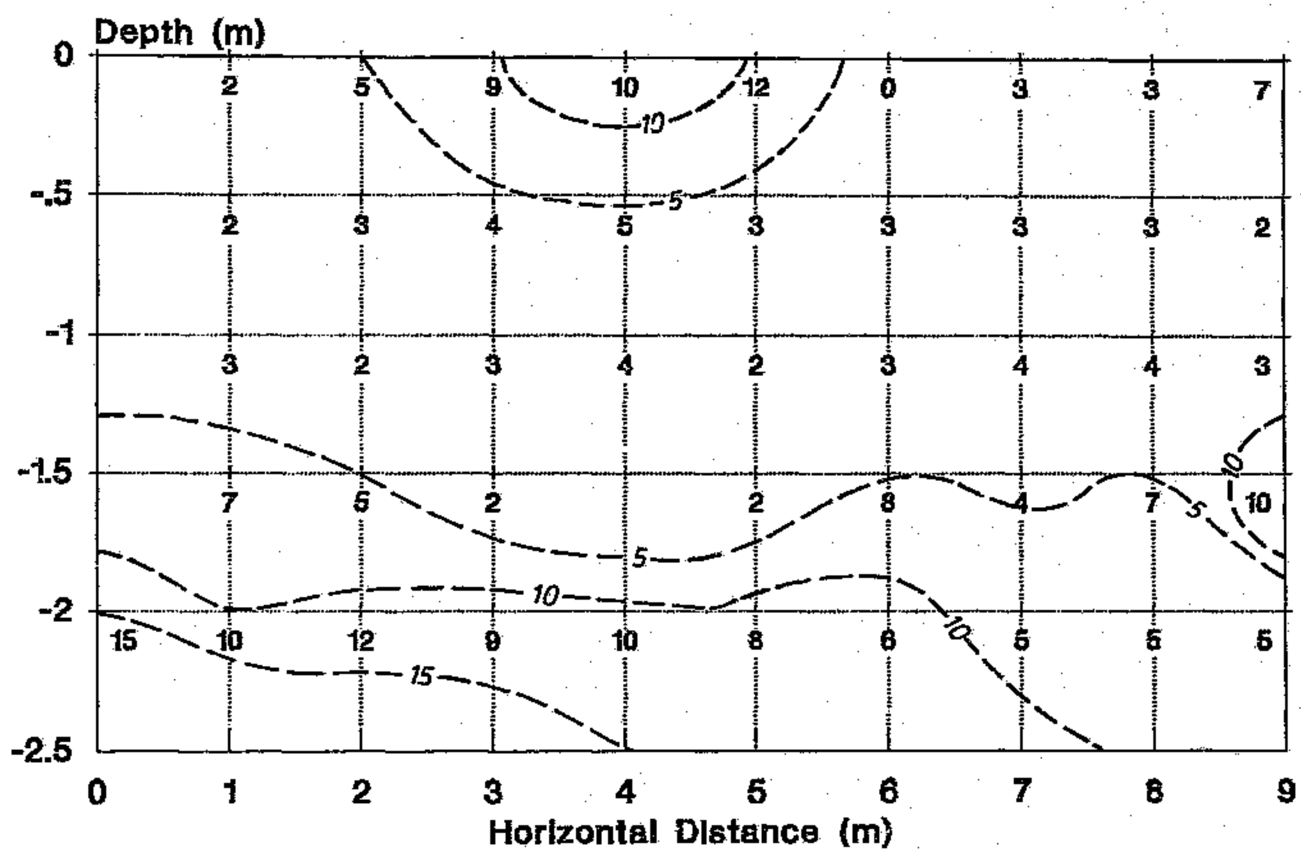


Figure 13.2 (g)
Coastal Park
Ammonia (as N, mg/kg dry solids) within the Unsaturated Zone

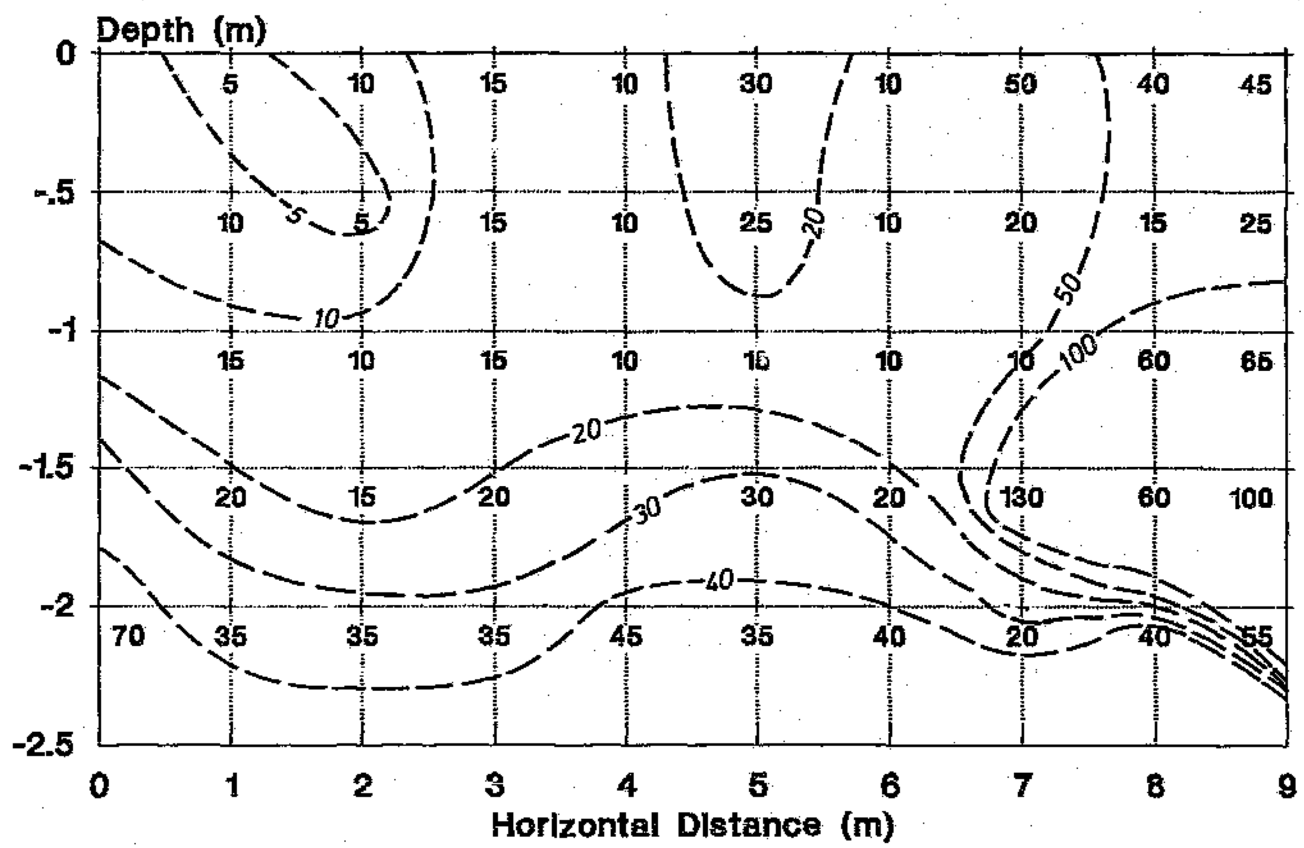


Figure 13.2 (h)
Coastal Park
Sulphates (as S, mg/kg dry solids) within the Unsaturated Zone

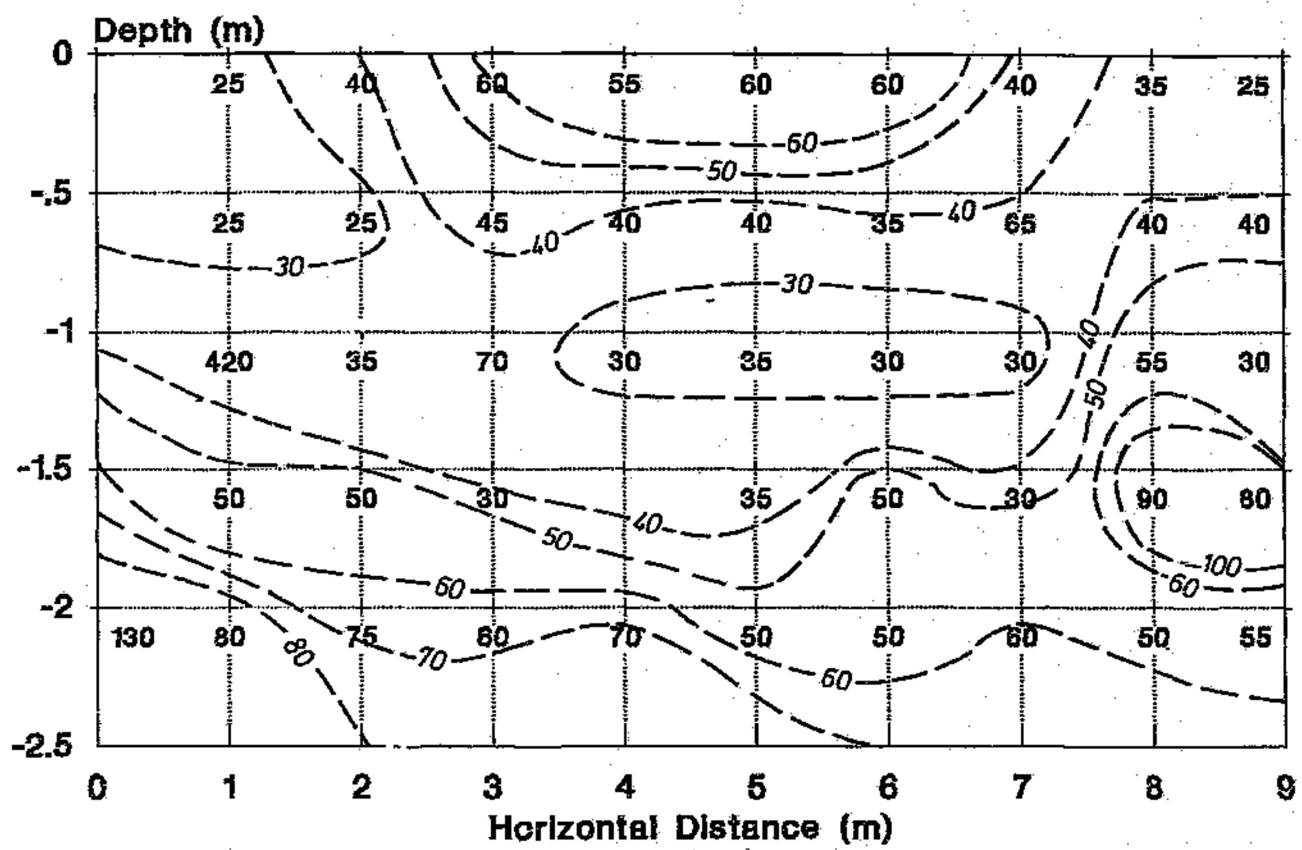


Figure 13.2 (j)
Coastal Park
Conductivity (mS/m) within the Unsaturated Zone

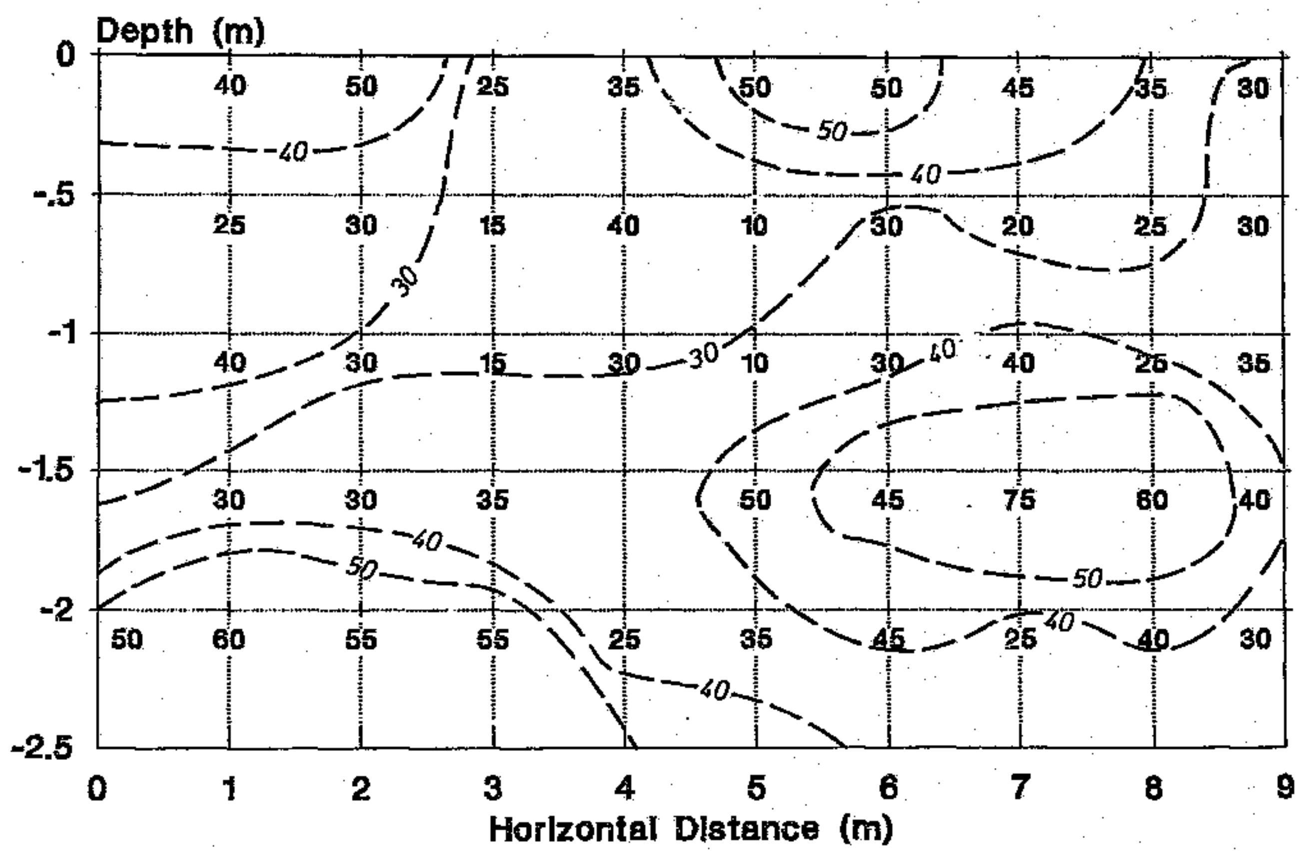


Figure 13.2 (k)
Coastal Park
Chemical Oxygen Demand (mg/kg dry solids) within the Unsaturated Zone

CONCLUSIONS AND RECOMMENDATIONS

World trends in the practice of landfilling municipal solid waste, and the design of landfill covers have been reviewed. The water balance principle has also been reviewed. Methods of evaluating each component of the water balance, (infiltration, evapotranspiration, the storage of water in porous media, and the movement of water in porous media,) have been reviewed.

A field study of the water balance has been carried out on Linbro Park landfill, situated in the Witwatersrand area.

Geotechnical and geohydrological properties of the landfill have been determined. These measured properties, together with existing, popular methods for calculating water balance have been used to estimate leachate production for the site. Moisture and contaminant migration studies, as well as infiltration studies have been carried out on this site. The data gathered from the field tests has been compared to theoretical predictions.

Moisture and contaminant migration within another landfill, situated near Cape Town, have also been studied.

Conclusions drawn from each part of the study are summarised below. Recommendations for further study in the field are put forward.

1 CONCLUSIONS

1.1 Moisture and Contaminant Migration

Moisture and contaminant migration within the landfill have been studied in several ways. Firstly by monitoring ground water quality (using boreholes situated around the landfill); secondly by analysing samples recovered from the landfill profile; and thirdly by using psychrometers to monitor in situ suction in the cover and upper refuse layers.

These studies have shown the following:

• The landfill appears not to be producing leachate at present.

• The concept of the landfill profile starting to drain only once field capacity has been reached, appears to be false. Moisture has been shown to move within the profile long before field capacity is reached.

• Given that moisture moves down the profile before field capacity is reached, and given the fact that the lower part of the landfill has been in place for about fifteen years, the landfill has probably already reached more or less steady state conditions. If the landfill is not producing leachate now, it is likely that it never will produce leachate.

• Methanogenesis appears to be occurring. Since the landfill is not producing leachate, this demonstrates that the minimisation of leachate does not necessarily prevent decomposition of the refuse and methane production.

• Contrary to methods popularly used to model moisture movement within landfills, one dimensional flow in a landfill is not dominant. Lateral flow has been found to be important. It appears that the deposition and compaction of refuse in layers, as well as the use of intermediate cover, and the presence of layers of plastic, gives rise to a series of 'aquifers' and 'aquicludes', which channel moisture movement in the direction of the slope of the original working face of the landfill.

• The popular concept that moisture can only be drawn out of a profile to a depth of about 300 mm is erroneous. The in- situ suction monitoring exercise has shown that evaporation extends to depths of at least 1 m. The sampling exercise has shown that evaporation may affect the entire profile, to a depth of at least 15 m.

• The idea that moisture cannot evaporate from the landfill cannot once it has passed through the cap, (because pores in the refuse may be too large to allow water to be drawn up by capillarity,) has been shown to be incorrect.

• The study of contaminant migration at Coastal Park landfill has added to the evidence that lateral flow is important in landfills. This study also shown that conditions found in test holes spaced some distance from one another are sufficiently similar to validate the use of fairly isolated sampling to predict the behaviour of a whole landfill.

1.2 Infiltration and Runoff

Infiltration into, and runoff from the surface of the landfill has been studied. A series of ring infiltrometer tests have been carried out. A sprinkler infiltrometer has been designed and built. Several sprinkler infiltrometer tests have been carried out using this apparatus. The findings of these tests are summarised below.

• Infiltration into the landfill cap under ponded conditions is very high indeed. This has been attributed to the presence of settlement cracks in the cover.

• The presence of cracks in the landfill surface appears to have little effect on runoff rates measured under conditions of light to moderate heavy rainfall. (It has been shown that 90% of rainfall event on the Witwatersrand fall into this category.) The SCS method, as adapted for South African conditions, was found to give good results for runoff predictions for this landfill. The data are, however too sparse to draw general conclusions about the accuracy of SCS runoff predictions for landfill surfaces.

1.3 Leachate Production Predictions

Calculations using simple gross water balance methods, as well as a popular landfill evaluation computer programme (HELP) were carried out. Predictions of leachate production vary between 40 % of the mean annual precipitation to zero. Although calculation methods underestimate the depth of the evaporative zone, and do not allow for lateral moisture flow, HELP's predictions appear to agree with conditions found in the field.

Numerous other methods of computing water balance, which may account for some of the short-comings mentioned above, exist. Time constraints, lack of data, and political restrictions have precluded carrying out analyses using these methods.

2 RECOMMENDATIONS

2.1 Geotechnical and Geohydrological Properties

The relationship between suction, moisture content and hydraulic conductivity for refuse is ill defined at present. Further testing to define these properties better would be valuable. The anisotropy of refuse compacted in layers should also be considered.

Better definition of these properties would assist in computations of landfill water balances, and could be used to carry out a water balance for the upper landfill layers on the basis of data gathered from the in-situ suction monitoring exercise.

2.2 Evapotranspiration

A comparison between predictions of evapotranspiration computed to allow for vapour movement, and the results of the field tests, would be useful.

2.3 Infiltration

The infiltrometer tests have shown that more data concerning the following aspects would be useful:

- An analysis of the intensity-depth-duration relationship for moderate to low rainfall events would be useful for rainfall simulation tests, and for runoff calculations.

- A comparison between the data measured during the sprinkler infiltrometer tests, and predictions of infiltration made using Richard's equation would be valuable.

- More sprinkler infiltrometer tests, carried out on a number of landfill covers of different nature need to be done so that the accuracy of using SCS predictions for computing runoff from landfill covers can be assessed more generally.

• A more detailed study of interception losses would improve estimations of infiltration.

• Measuring runoff during a number of natural rainfall events would be valuable, to see how well the sprinkler infiltrometer performs in its simulations.

• A few tests measuring infiltration under very high intensity rainfall would be valuable Although high intensity rainfalls, occur relatively infrequently, they may account for a large percentage of the annual precipitation. The effect of cracks in the landfill cover may be more important at higher intensity rainfalls.

2.4 Moisture Movement

Computer programmes which simulate two dimensional flow, and so take account of soil anisotropy, could be used to model the water balance. A comparison between the calculated results and data obtained from the field would be useful.

2.5 Contaminant Migration

The sampling exercise of the toe of the Coastal Park landfill needs to be repeated in order to draw conclusions about the movement of contaminants in the unsaturated zone.

There appears to be little point in coupling convective-dispersive equations (to describe movement of contaminants within the landfill) to water balance calculations at this stage, since predictions of moisture migration are not yet accurate.

2.6 Cover Design

It has been demonstrated that given suitable climatic conditions, a simple soil cover may be sufficient to eliminate leachate production. Tests on cover design in areas that have wetter climates, should be carried out to establish the potential of covers to eliminate leachate under less favourable climatic conditions.

Landfill covers should not be sloped inwards to prevent runoff from the dump, in accordance with the Water Act of 1956. The runoff should be collected separately, and checked for contamination before being discharged.

A study on the effect of slope on the erosion of landfill covers would be useful.

Substantial evidence to suggest that landfill covers can eliminate leachate production, and so obviate the need for landfill liners and leachate collection and treatment systems has been presented.

Computer programmes which are popularly used for evaluating the performance of covers in the water balance could be substantially improved. Methods of calculation that might improve the accuracy of predictions exist, but need to be tested and presented in a form which would facilitate the evaluation of landfill covers for design purposes. Additional information on the geohydrological properties of refuse would aid in water balance calculations.

APPENDIX A

DETERMINATION OF REFUSE MOISTURE CONTENT

The moisture content of refuse was determined by oven-drying a sample at 50°C for seven days. The sample attained a constant mass after seven days.

This procedure is used rather than drying at 100°C for 24 hours, (as is common practice for soils) to minimise the loss of volatile organics while drying the sample.

Moisture contents are quoted as the ratio of mass of water to mass of solids, (unless otherwise stated.)

APPENDIX B

EXTRACTION OF LIQUOR FOR CHEMICAL ANALYSIS

Extracts from soil and refuse samples, for chemical analysis were prepared as follows:

500 mℓ of distilled water (at 18°C) was added to 2 kg of refuse. The mixture was then vibrated at a frequency of 50 Hz for 30 minutes. The supernatant liquor was then drained through a coarse filter, into a clean bottle. This process was repeated twice.

The liquor thus extracted was then centrifuged at 9000 rpm for 10 minutes, to remove suspended solids. It was then stored in the refrigerator at 4°C until it was sent to Johannesburg's Department of Health laboratories for chemical analysis.

The extraction process used was developed by Hojem, 1988. It has been used as a standard for comparative evaluation of the pollution potential of refuse at the Coastal Park and Linbro Park sites, in subsequent years.

The results from the laboratory were given in mg/ℓ of the liquid sent for analysis. To ensure that comparisons were consistent, the results were converted to mg/kg of dry refuse.

The results of the chemical analyses for samples recovered from Linbro Park, and Coastal Park are given in tables B1, B2, and B3.

ANALYSIS OF SAMPLES FROM LINBRO PARK LANDFILL (NOVEMBER 1990)
(Results in mg/kg dry refuse)**

HOLE	pH	Conductivity mS/m	TDS	COD	Alkalinity	SO4	NH4	Cl	K	Na	NO3	Water Content
NC 0m	7.6	88	249	91	132	155	5	205	32	70	0	3
N 1m	7.9	273	203	54	32	83	1	34	34	5	0	19
SC 0m	6.8	108	165	33	0	44	2	200	8	64	1	2
S 1m	7.3	349	525	1923	507	dark*	172	399	188	98	0	28
S 2m	8	266	1238	723	627	dark*	135	251	125	30	0	17
S 3m	7.3	770	1230	4523	1346	dark*	209	717	915	329	0	111
S 4m	8	836	1208	3723	1464	dark*	320	914	1080	300	0	87
S 5m	7.5	992	1380	5108	1692	dark*	348	1055	795	329	0	95

*"dark" indicates that sample was too dark in colour to carry out analysis
** except for pH, conductivity, and water content (water content in % of dry mass)

Table B1
Results of Chemical Analyses of Extracts of Samples Recovered from Linbro Park Landfill

ANALYSIS OF SAMPLES FROM COASTAL PARK LANDFILL (April 1990)
(Results in mg/kg dry refuse)

HOLE	pH	Conductivity mS/m	TDS	COD	Alkalinity	SO4	NH4	Cl	K	Na	NO3	Water Content
alpha 2m	8.1	187	2269	62	130	22	0	173	57	182	106	50
alpha 3m	8.1	252	1543	334	471	dark	4	309	220	221	6	16
alpha 4m	8.4	416	3341	528	1557	81	145	659	126	326	0	52
alpha 5m	7.8	381	4696	1332	1016	dark	20	1076	782	735	0	139
alpha 6m	7.5	862	6286	2582	1117	dark	0	2544	526	1036	0	23
alpha 7m	7.8	318	2235	413	221	270	0	530	278	319	121	
beta 0-1m	7.8	205	1841	93	108	84	0	73	58	46	147	18
beta 1-2m	7.5	763	6546	2944	dark	dark	dark	dark	dark	dark	dark	22
beta 2-3m	8.3	445	3223	495	775	85	11	806	108	300	0	36
beta 3-4m	8	234	1861	417	477	116	10	259	86	243	1	8
beta 4-5m	7.6	535	3621	1157	488	dark	7	712	539	484	0	17
beta 5-6m	7.9	100	2027	76	54	11	0	194	108	143	136	13
gama 0-1m	7.9	129	834	40	128	93	0	98	51	65	40	7
gama 1-2m	8.1	219	1170	161	285	167	3	143	80	88	3	
gama 3-4m	7.8	676	1868	626	548	63	1	451	354	256	3	18
gama 4-5m	8.4	54	2906	539	391	311	2	802	132	133	1	34
gama 5-6m	7.4	431	2913	754	477	300	0	883	115	117	0	18
gama 6-7m	8.8	240	1818	618	545	dark	6	192	163	146	19	6

*"dark" indicates that sample was too dark in colour to carry out analysis
** except for pH, conductivity, and water content (water content in % of dry mass)

B2

Results of Chemical Analyses of Extract[illegible] [illegible]mples Recovered from Coastal Park Landfill

ANALYSIS OF SAMPLES FROM TOE OF COASTAL PARK LANDFILL (April)
(Results in mg/kg dry refuse)**

Hole	pH	Conductivity mS/m	TDS	COD	Alkalinity	SO4	NH4	Cl	K	Na	NO3	Water Content
A 2m	8.1	129	931	49	37	70	0	104	64	82	50	24
B 0m	8.2	27	146	40	34	4	0	5	5	4	8	7
B 0.5m	8.1	26	110	26	49	10	0	5	6	5	8	5
B 1m	7.6	420	253	40	49	15	0	6	10	7	10	6
B 1.5m	8	50	279	29	47	22	0	17	22	16	25	10
B 2m	8.2	80	556	59	27	36	0	91	36	52	34	22
C 0m	7.6	42	79	48	46	8	0	17	6	13	17	5
C 0.5m	8.2	26	145	28	47	6	0	5	5	6	10	7
C 1m	8.2	35	268	32	77	8	0	8	9	9	7	5
C 1.5m	8	50	296	37	44	11	0	25	14	24	24	10
C 1.5m	7.8	57	279	25	58	16	0	16	10	13	13	10
C 2m	7.9	77	186	55	50	35	0	64	105	42	41	21
D 0m	8	62	412	24	72	15	0	10	8	13	32	6
D 0.5m	8.1	44	250	16	59	13	0	8	7	13	14	4
D 1m	8.3	72	ERROR	16	59	13	0	10	8	13	10	6
D 1.5m	8.1	31	169	37	43	21	0	11	8	9	7	10
D 2m	8.2	62	464	55	31	35	0	44	33	31	31	22
E 0m	7.8	53	397	36	67	9	0	10	4	10	33	6
E 0.5m	7.9	38	248	39	43	9	0	8	5	9	17	5
E 1m	8.4	28	183	28	29	9	0	4	4	6	14	5
E 2m	7.5	71	458	27	47	46	0	47	29	33	33	22
F 0m	7.9	62	463	49	28	29	0	14	12	13	41	8
F 0.5m	8.2	42	269	12	59	25	0	7	10	10	10	6
F 1m	8.2	34	143	8	62	17	0	7	13	9	7	6
F 1.5m	7.9	36	64	52	56	29	0	25	13	14	7	14
F 2m	8.1	50	490	36	74	33	0	44	25	30	27	21
G 0m	7.9	60	289	52	197	10	0	8	10	10	0	7
G 0.5m	8.1	35	240	28	49	11	0	8	10	8	15	7
G 0.5m	7.8	34	192	12	67	21	0	6	10	9	8	7
G 0.5m	7.6	53	335	28	67	11	0	13	12	12	30	7
G 1m	7.5	36	191	36	68	11	0	9	14	10	9	6
G 1m	8.3	30	111	32	45	44	0	5	8	5	10	6
G 1.5m	8.2	47	361	48	60	25	5	131	25	24	8	9
G 1.5m	8.3	60	373	41	33	16	0	43	32	31	30	9
G 2m	8.2	50	416	45	46	40	0	43	24	30	20	21

** except for pH, conductivity, and water content (water content in % of dry mass)

Table B3

Results of Chemical Analyses of Extracts of Samples Recovered from Toe of Coastal Park Landfill

ANALYSIS OF SAMPLES FROM TOE OF COASTAL PARK LANDFILL cont
(Results in mg/kg dry refuse)**

Hole	pH	Conductivity mS/m	TDS	COD	Alkalinity	SO4	NH4	Cl	K	Na	NO3	Water Content
H 0m	7.9	40	383	44	138	50	0	9	6	11	9	6
H 0.5m	8.3	63	251	20	74	19	0	5	7	12	12	5
H 1m	8.1	30	203	39	31	10	0	4	6	5	14	4
H 1.5m	7.9	30	583	73	38	130	0	32	25	23	15	11
H 2m	7.9	60	329	27	55	20	0	41	16	30	17	22
I 0m	8.1	37	226	36	28	39	0	6	5	8	12	5
I 0.5m	8.1	39	250	23	56	16	0	5	5	7	10	4
I 1m	8.3	55	376	27	102	59	2	4	6	7	8	4
I 1.5m	7.8	88	502	62	88	58	0	150	16	18	23	12
I 2m	8.1	51	344	42	43	38	0	44	16	30	16	26
J 0m	7.9	25	443	28	100	47	0	5	4	5	24	5
J 0.5m	8.1	38	186	31	49	26	0	4	3	6	8	3
J 1m	8	28	252	36	40	63	0	4	8	5	9	5
J 1.5m	7.7	80	641	42	46	99	0	13	11	16	34	13
J 2m	8.2	57	386	32	53	55	0	30	11	24	16	23
T 1m	8.1	53										
T 1.5m	7.8	64										
T 2m	8.1	27										

** except for pH, conductivity, and water content (water content in % of dry mass)

Table B3 (continued)
Results of Chemical Analyses of Extracts of Samples Recovered from Linbro Park

APPENDIX C

FIELD CAPACITY TESTS

The volume of sample available for field capacity tests was generally small. CBR moulds (152 mm in diameter, and 152 mm deep) were used to contain the sample.

The moulds have a perforated base plate. A sheet of filter paper was placed over the perforations to prevent loss of solids. Refuse was then placed loosely in the moulds, flooded, and left to drain for 24 hours. During this period, the mould was covered to prevent evaporation. The samples were then tested.

An Amsler loading machine was used to compress the samples. The water which was squeezed out was collected, and its volume measured at intervals during the loading. At these points, the height of the sample, and the applied load was also recorded, so that the stress and density corresponding to a given field capacity could be computed. Care was taken to ensure that the sample had completely drained when the measurements were taken.

At the end of the test, the moisture content of the sample was determined. Moisture contents at field capacity, at different densities, were then calculated.

Examples of results of the field capacity tests performed on samples recovered from the landfills, are shown in figures C1 to C7.

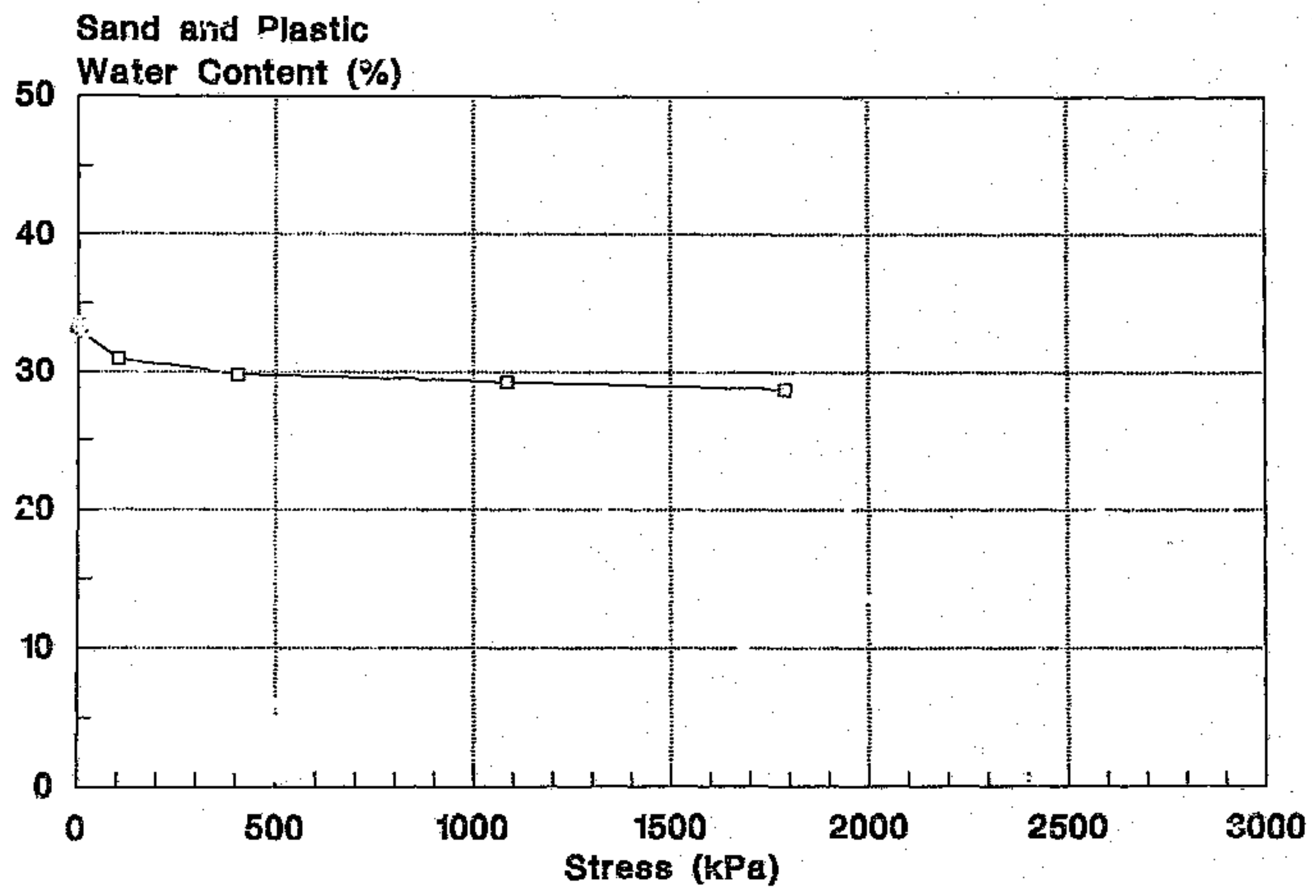


Figure C1
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 0m - 1m)

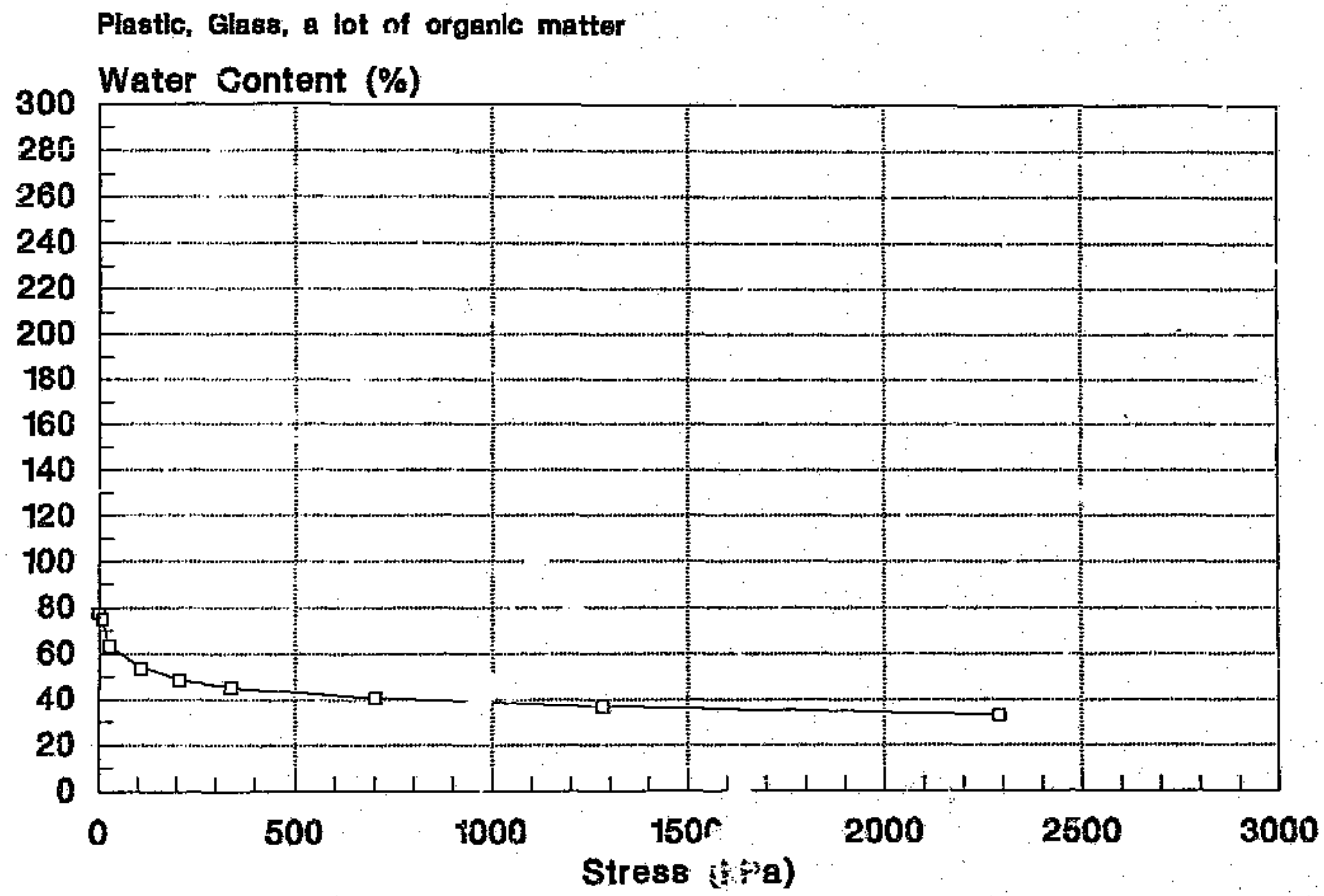


Figure C2
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 1m - 2m)

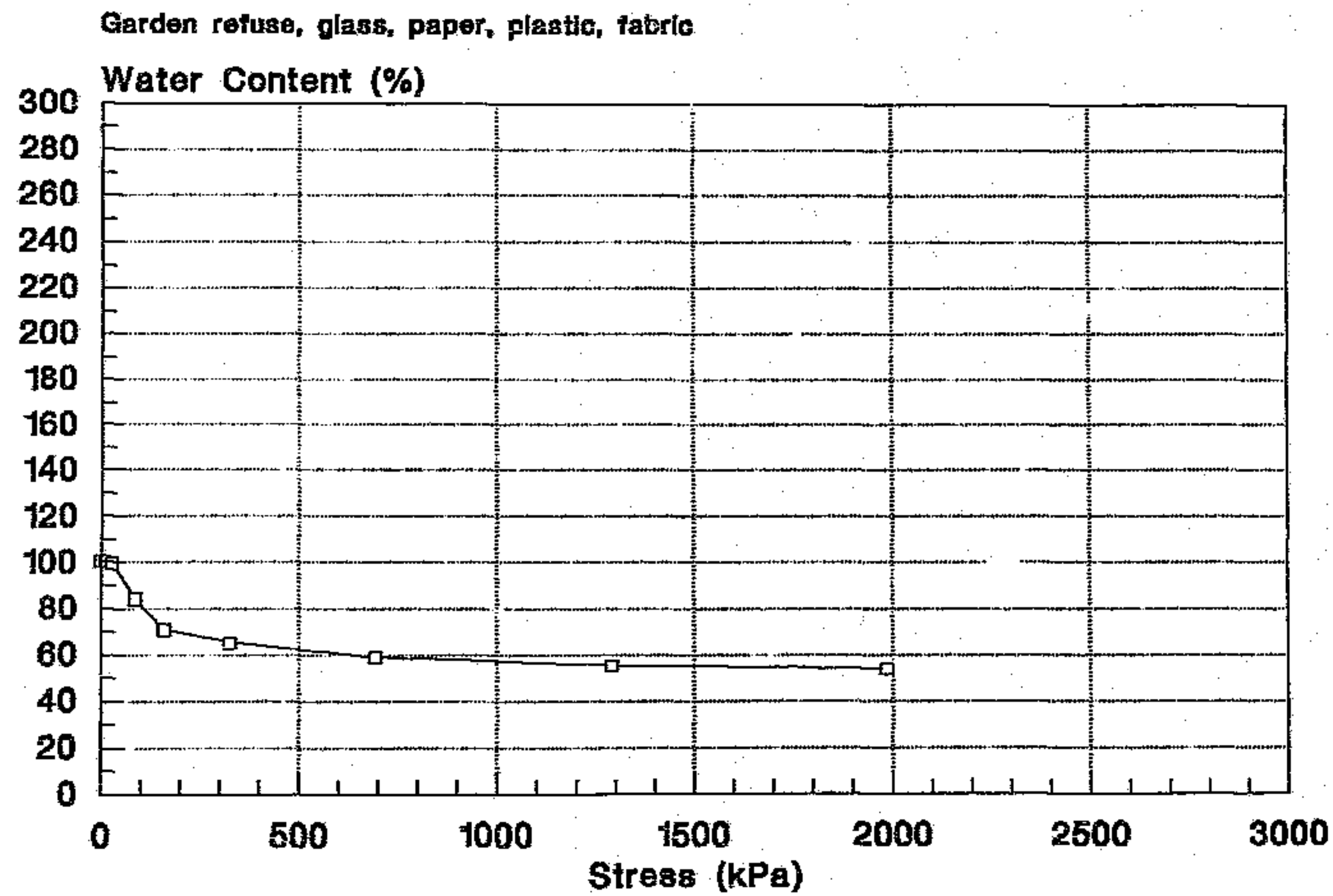


Figure C3
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 2m - 3m)

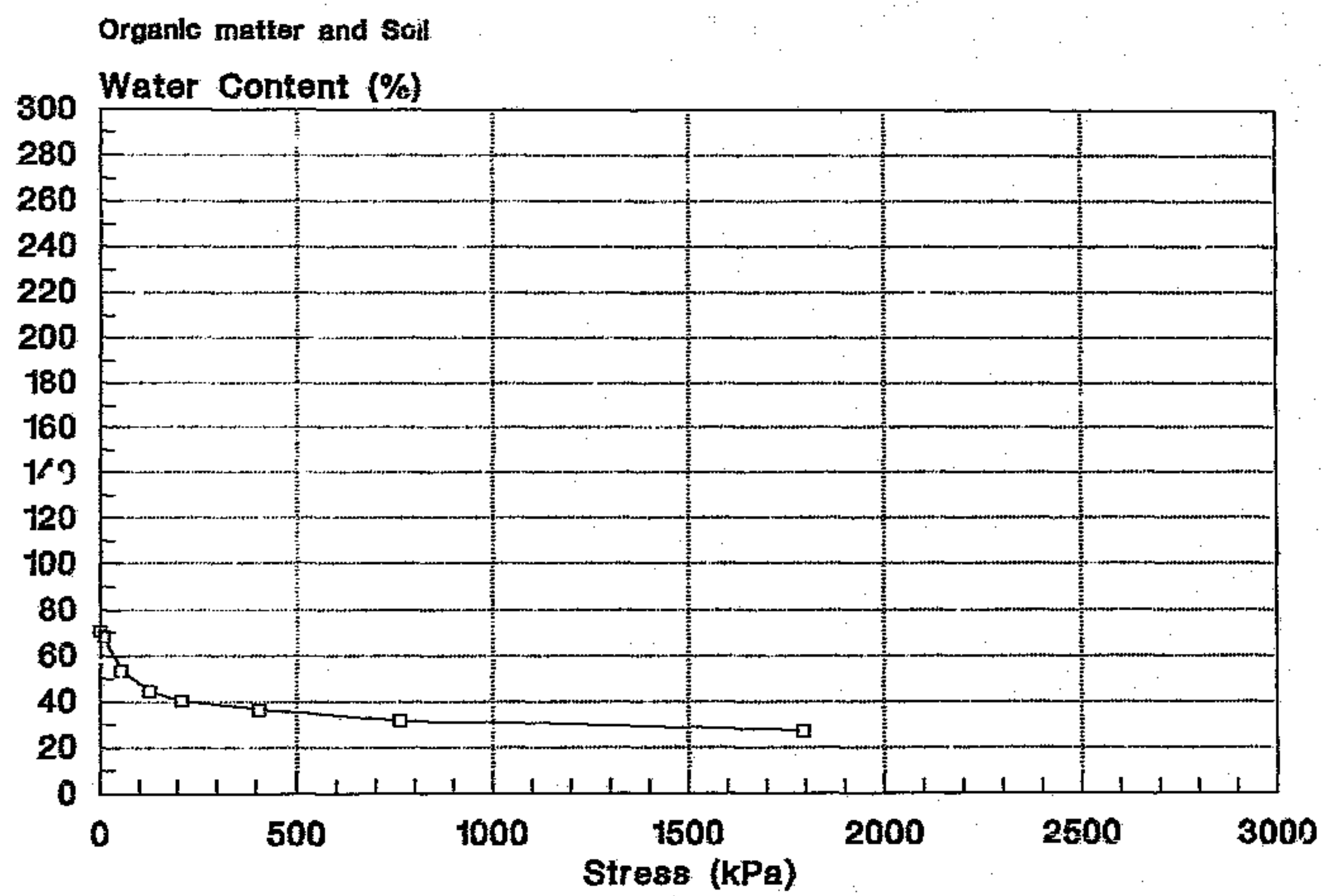


Figure C4
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 3m - 4m)

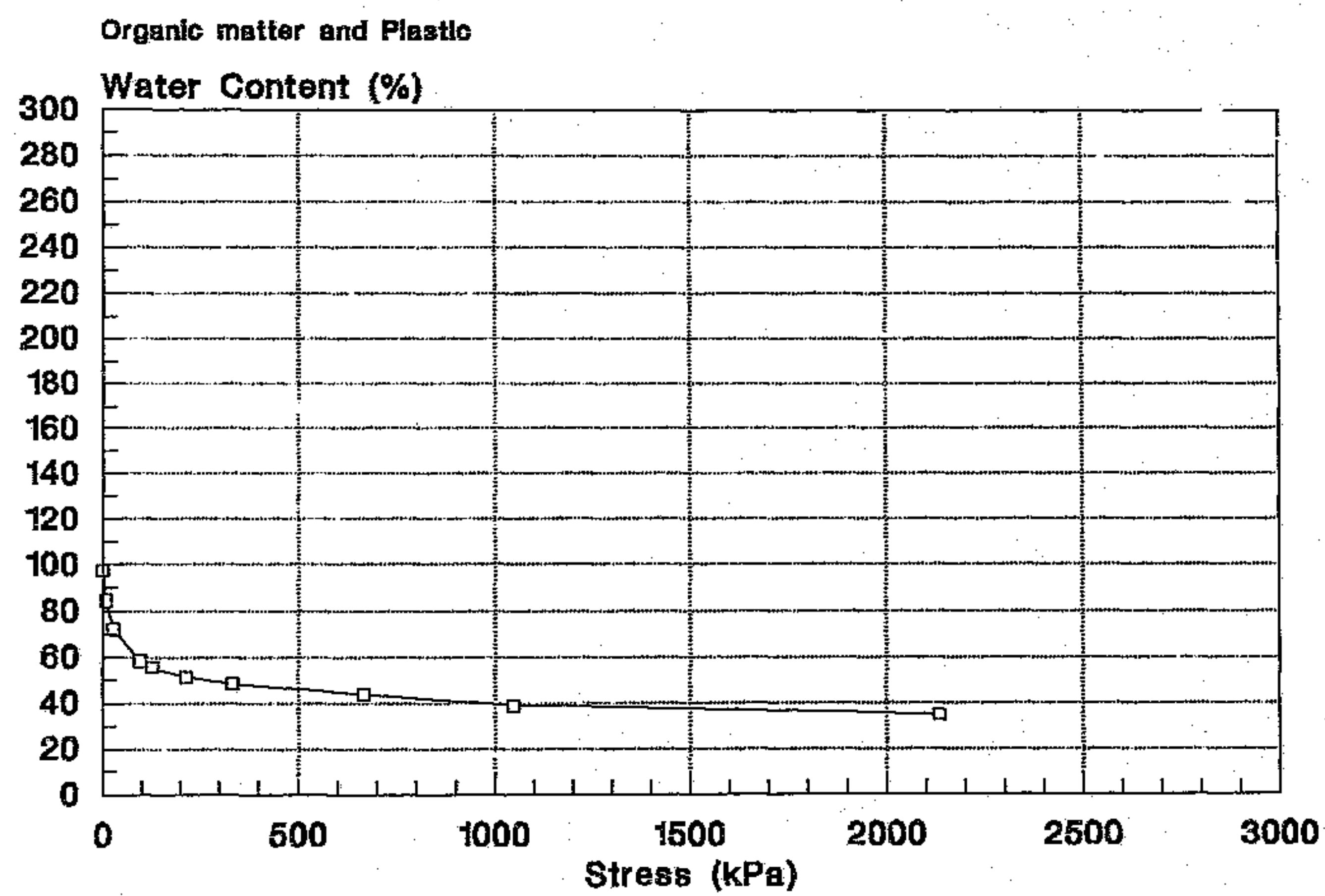


Figure C5
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 4m - 5m)

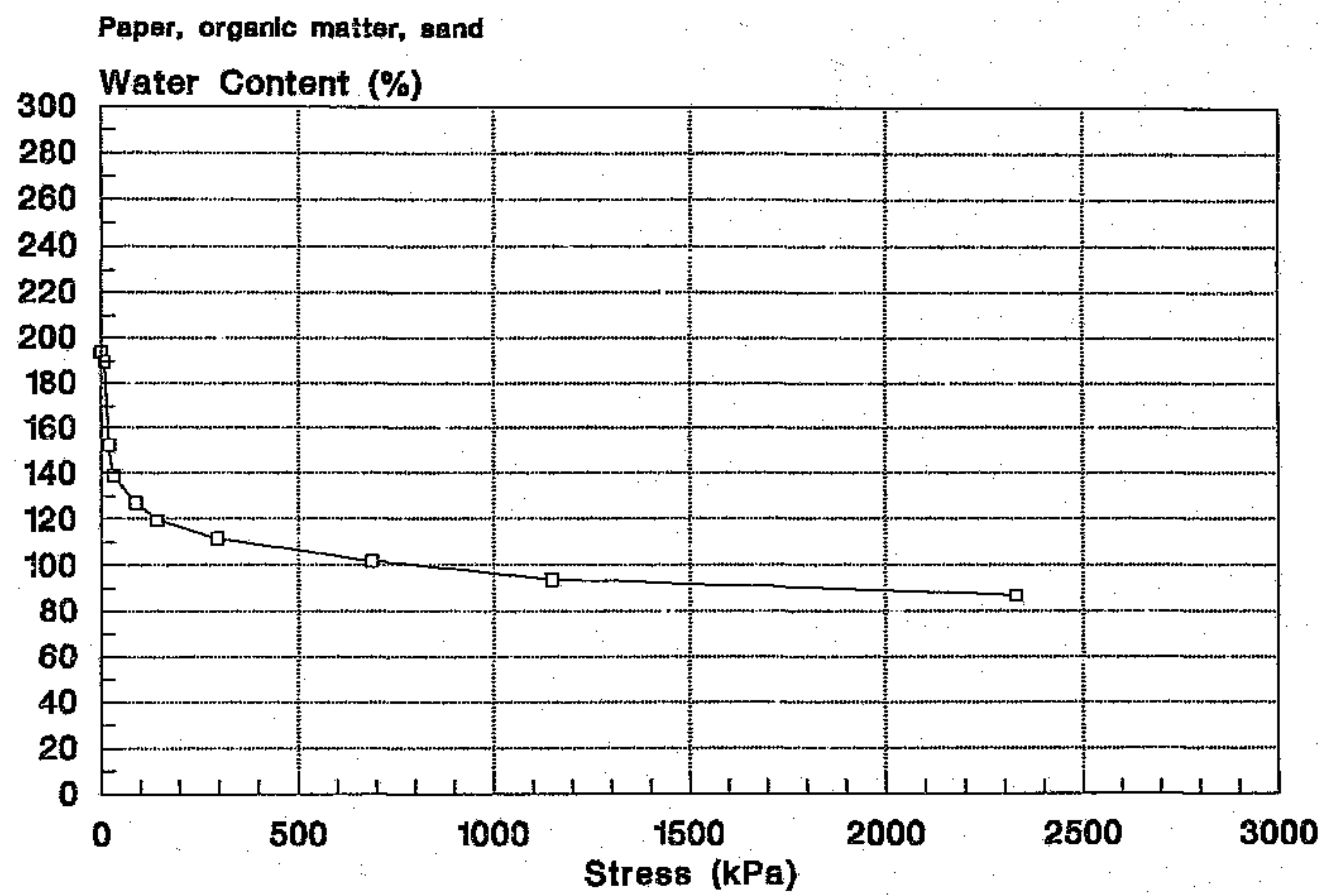


Figure C6
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 5 m - 6m)

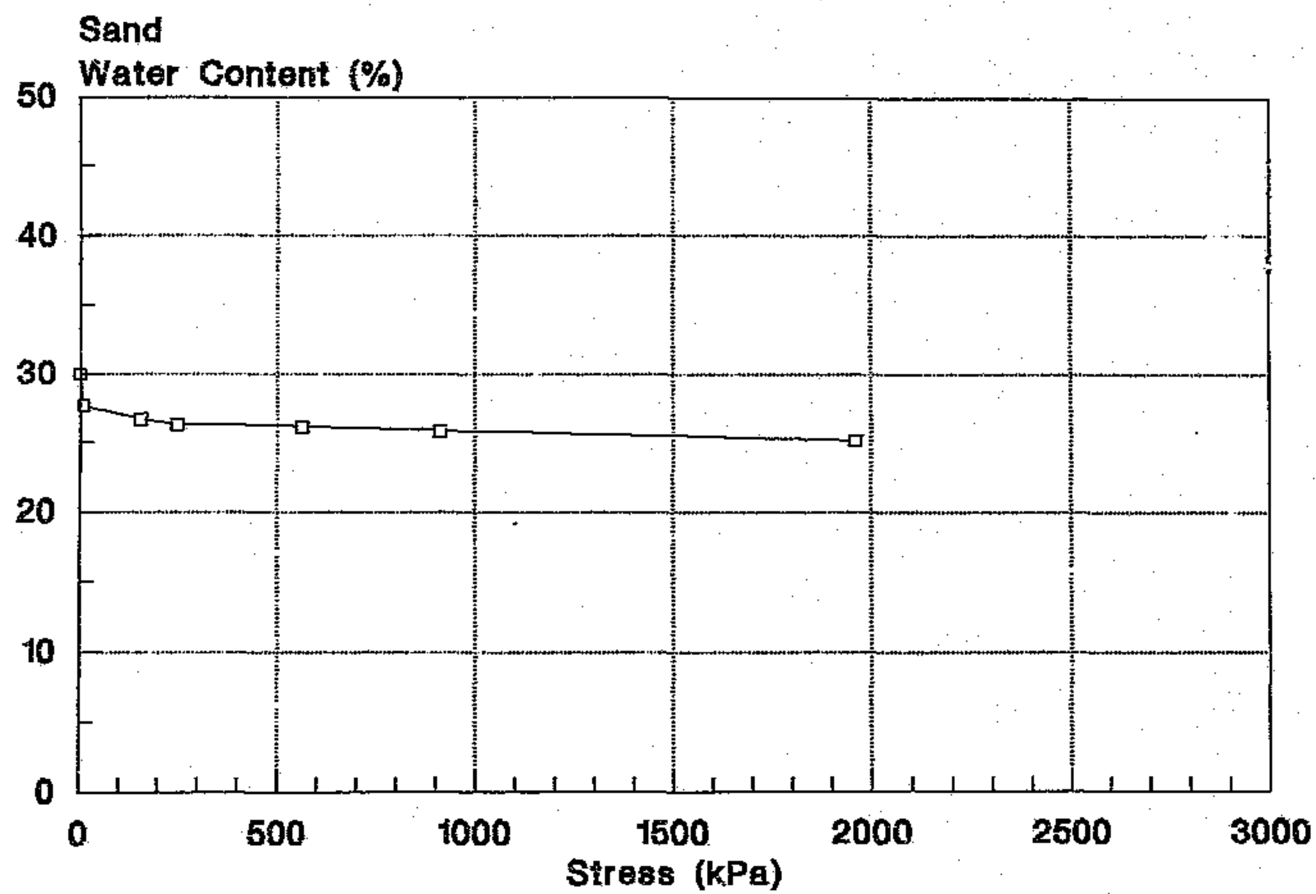


Figure C7
Results of Field Capacity Test for Coastal Park Landfill, Hole Gamma (depth 6m - 7m)

APPENDIX D

LABORATORY SUCTION TESTS

Immediately after the samples had been recovered, they were placed in tightly sealed plastic bags. The bags were taken to the laboratory, where they were placed in an insulated room, in which the temperature is kept constant at 25°C.

A thermocouple psychrometer was inserted into each bag, and allowed to equilibrate for 24 hrs.

The psychrometers were read, for 2 to 3 days in sucession. Repeatable results were usually obtained during this period.

A Wescor PR-55 control box was used to read the instruments. A standard cool time and cool current of 8mA was used. The control box was connected to an x-t recorder so that the output from each psychrometer could be analysed.

APPENDIX E

CALIBRATION OF PSYCHROMETERS AND FILTER PAPER

1 PSYCHROMETERS

When using psychrometers to take suction measurements, each psychrometer should, strictly speaking, be individually calibrated, at a number of suctions, for the particular cool time and the particular cool current w' .. is to be used.

A calibration curve for each psychrometer, for one suction, one cool time, and one cool current is supplied by the manufacturer. The relationship between voltage output from the psychrometer, and suction is nearly linear, (Wescor, 1990.) It is therefore possible to calculate suction over the entire operational range of a psychrometer, from a single point calibration point.

Strictly speaking, suction measurements should be corrected for temperature effects if the measurements are made at temperatures different to those at which the instruments were calibrated. These corrections, however, amount to a small percentage of the reading. (About 0.5% per °C)

The calibrations for individual psychrometers of the same design are similar. They have been found in this project to be within 10% of one another. (This is based on the manufacturer's calibration.)

To calibrate each individual psychrometer over a range of 5000 kPa is a time consuming and tedious process, especially if a large number of psychrometers are to be used. A small calibration exercise was carried out to ascertain whether it would be worthwhile calibrating each psychrometer over a range of 5000 kPa, or whether using the average of the manufacturer's results would suffice.

Some of the psychrometers used in this project had been used before. It was suspected that some of these may have been contaminated or corroded. Even new psychrometers may become contaminated during calibration by the manufacturer. Each psychrometer head was carefully cleaned before the calibration exercise, and before installation in the field.

Corrosion products were removed by dipping the psychrometers alternatively in ammonium and distilled water. Oily contaminants were removed by dipping the psychrometers alternatively into acetone, and distilled water. The psychrometers were examined under a microscope to ensure that they w... ...an.

The psychrometers were calibrated against solutions of sodium chloride. The suctions of sodium chloride solutions at various temperatures are quoted by Wescor, 1990, (as calculated by Lang, 1967.)

Two sets of measurements were made. Readings were repeated several times. Successive readings matched closely. The readings were taken using a Wescor PR 55 control box. The box was connected to an x-t voltage recorder. It was found that the psychrometer output could be more accurately interpreted by examining the graphical output, than by simply using the reading recorded on the control box. (The box takes a reading a set time after the cool current has passed through the psychrometer.) Care was taken to ensure that 'short' readings did not exceed 2 mV.

A variety of different psychrometers was used in the first set of measurements, each psychrometer being used to measure the suction of a different solution. Suction was calculated from the voltage output of the psychrometers by using the average of the manufacturer's calibrations (of 15 psychrometers.)

The second set of measurements were taken using only one psychrometer. Suction was calculated from the output from the psychrometer using the manufacturer's calibration for that particular psychrometer.

The calculated values of the suction of the sodium chloride solutions were plotted against the suctions calculated using the manufacturer's calibration. (See figure E1.) The line of best fit for the data has been drawn in. The line which represents a perfect correlation is also shown.

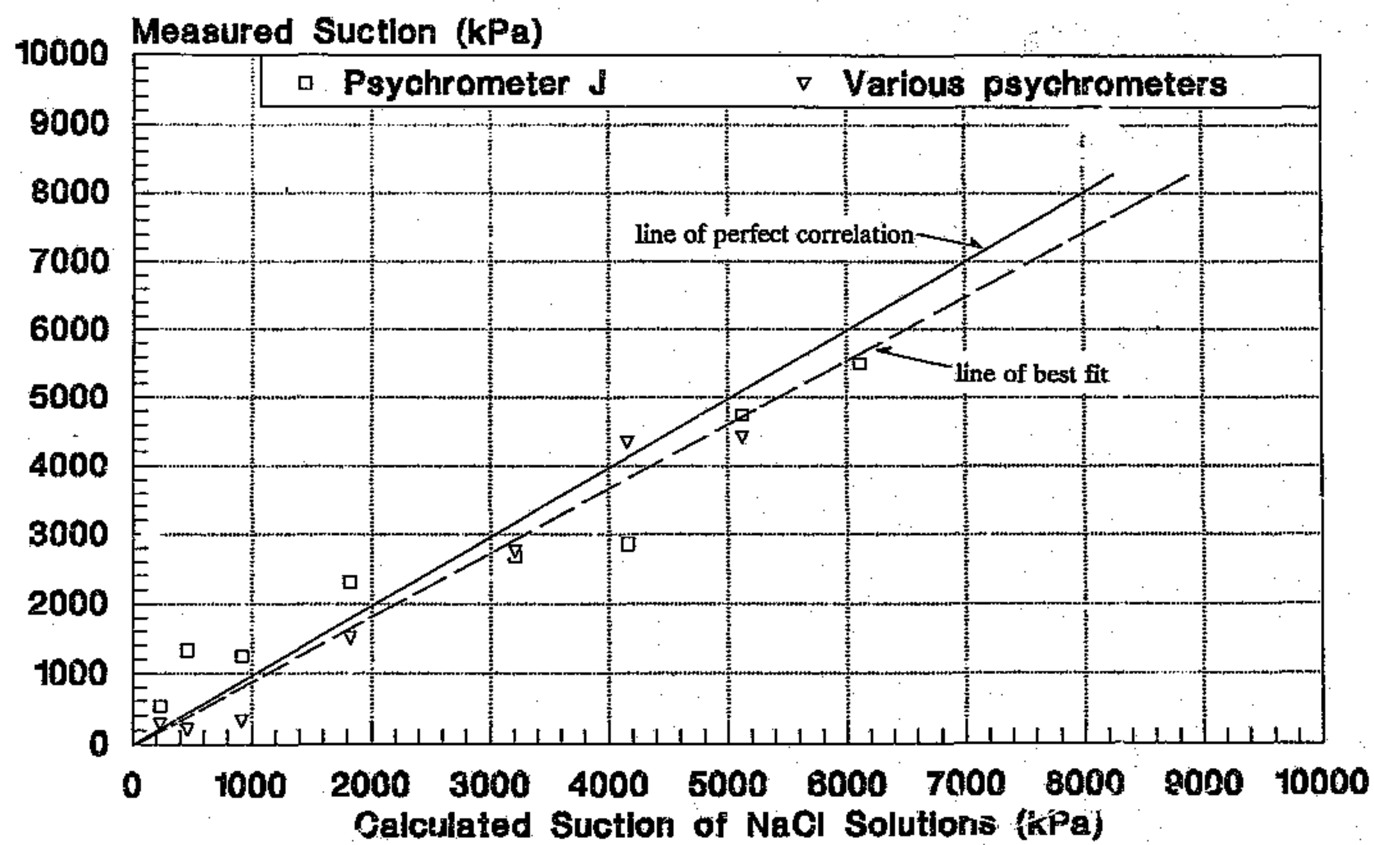


Figure E1
Calibration of Psychrometers Against Sodium Chloride Solutions

The magnitude of error for the set of various psychrometers was found to be 360 kPa, while the magnitude of error for the single psychrometer was found to be 600 kPa. If the readings are corrected according to the line of best fit, the errors are reduced to 320 kPa, and 520 kPa respectively. At the upper end of the range of the psychrometers (5000 kPa) this represents an accuracy of 5% to 10%. At low suctions (500 kPa), results are accurate only to within 100%.

Savage and Scholes, 1989, report that individually calibrated psychrometers give results accurate to within 25 kPa, while, psychrometers which are not individually calibrated give readings accurate to within 15%. In this exercise, however, no better accuracy was obtained using a single psychrometer, than was obtained using a variety of psychrometers, and average calibration figures.

On the basis of these results, the psychrometers were not calibrated over the entire suction range for the field tests, but the manufacturer's calibrations were used.

2 FILTER PAPER

A calibration exercise for suction measurements using filter paper was carried out. Strips of Whatman No 42 filter paper were used. The strips were 25 mm long and 5 mm wide.

The strips were allowed to equilibrate with a series of salt solutions of different suctions, for a period of a week. At the end of the week, their moisture contents were determined. Suctions were calculated from the moisture contents, based on Savage's calibration (Savage, 1991). These results were plotted against the calculated suctions of the salt solutions. The results are shown in figure E2. A very poor correlation between measured and calculated suction was obtained.

Strips of filter paper were also allowed to equilibrate with soil samples of given moisture contents. The samples were prepared in the laboratory. The soil was initially dried to a moisture content of about 2 %. The moisture content was then adjusted for each sample, by adding water. The samples were compacted using static compaction. Samples of two different densities were used.

The moisture content of the filter paper was determined after a period of equilibration of a week. The moisture contents of the paper were plotted against the moisture contents of the soil samples. The results are shown in figure E3. There is a poor correlation between the two moisture contents.

Based on the results of this calibration exercise, it was decided that psychrometers should be used for suction measurements in the field tests.

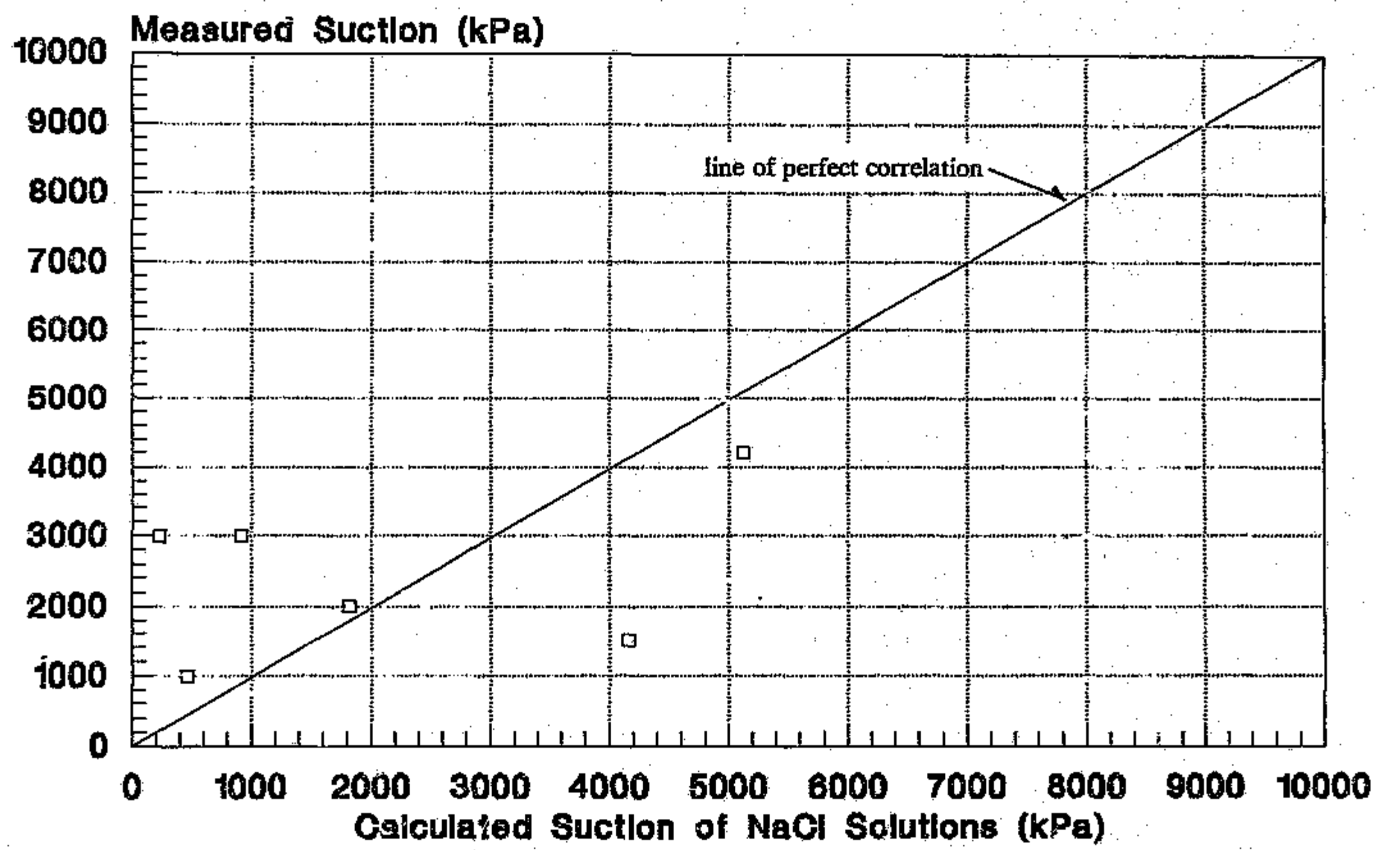


Figure E2
Calibration of Whatman No 42 Filter Paper Against Sodium Chloride Solutions

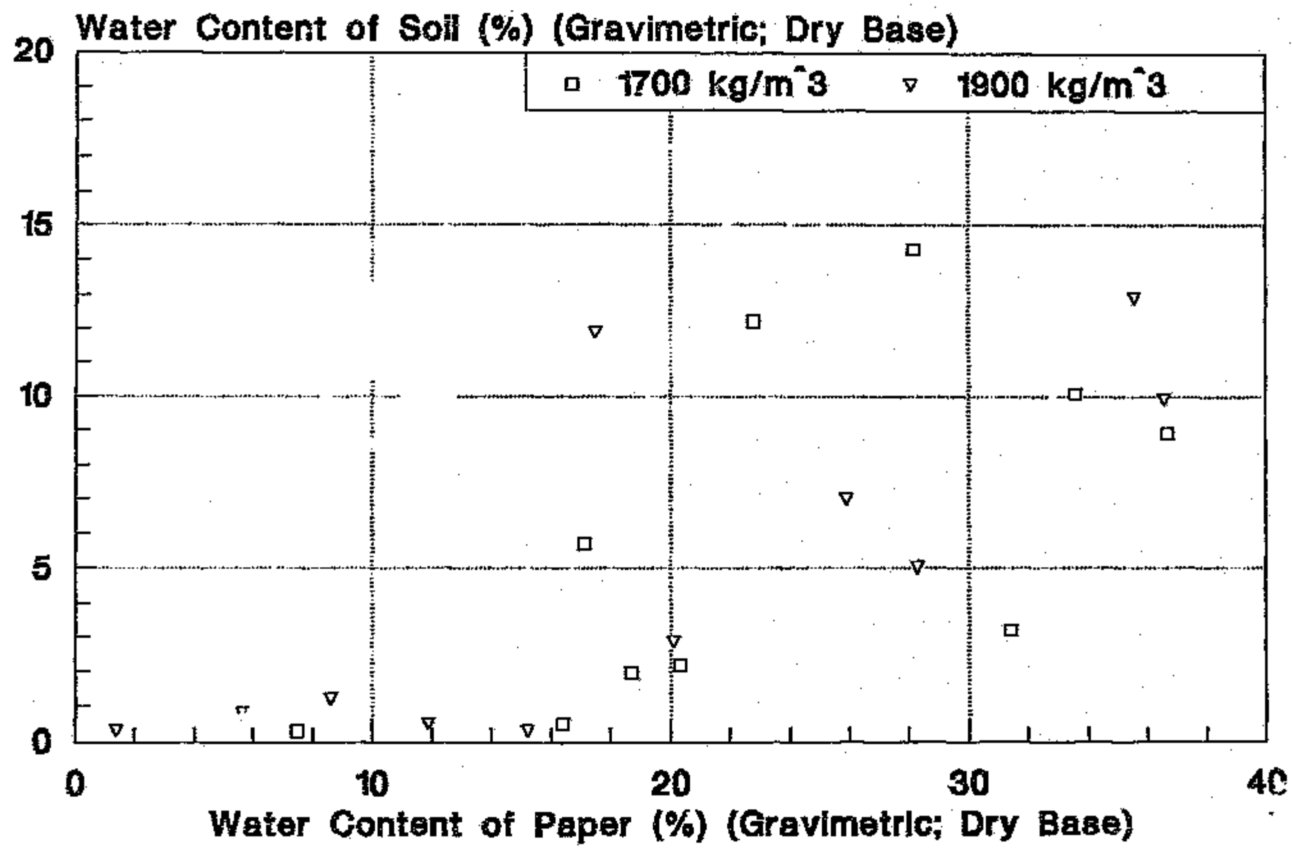


Figure E3
Correlation Between Moisture Contents of Filter Paper and Soil Samples

APPENDIX F

DOUBLE RING INFILTROMETER TESTS - METHOD AND RESULTS

The dimensions of the infiltrometer rings used are as follows: Outer ring: 1000 mm in diameter Inner ring: 600 mm in diameter

A laboratory test was carried out to ensure that one-dimensional infiltration could be achieved using rings of these proportions.

A scale model of the rings was constructed and placed in a perspex tank full of soil. Water dyed with potassium permanganate was used to fill the inner ring of the model. The outer ring was filled with undyed water.

The model test showed that during the initial stages of a double ring infiltrometer test (using rings of these proportions,) lateral flow may be significant, but that during later stages of the test, one dimensional infiltration from the inner ring, is achieved.

The early and later stages of the model test are illustrated in figures F1 and F2.

To perform the field tests, the rings were driven 10 mm to 20 mm into the ground, using a hammer. The edges of the ring were then sealed with gypsum. The water levels in the two rings were kept equal throughout the tests. The rings were covered to prevent evaporation.

Figures F3 to F8 show the results of the infiltrometer tests, carried out on four different sites. The results have been summarised and discussed in Chapter 10.

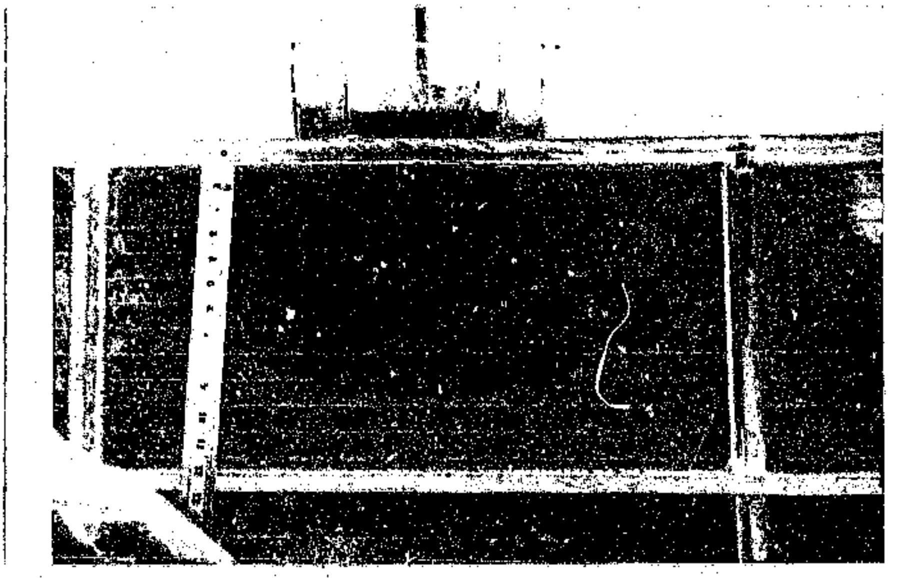


Figure F1
Infiltration During the Early stages of
The Double Ring Infiltrometer Model Test

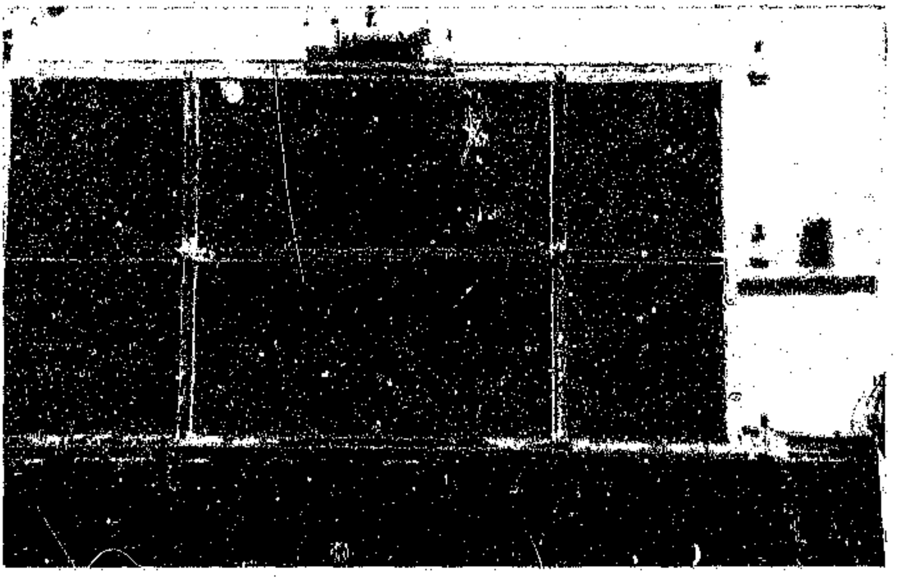
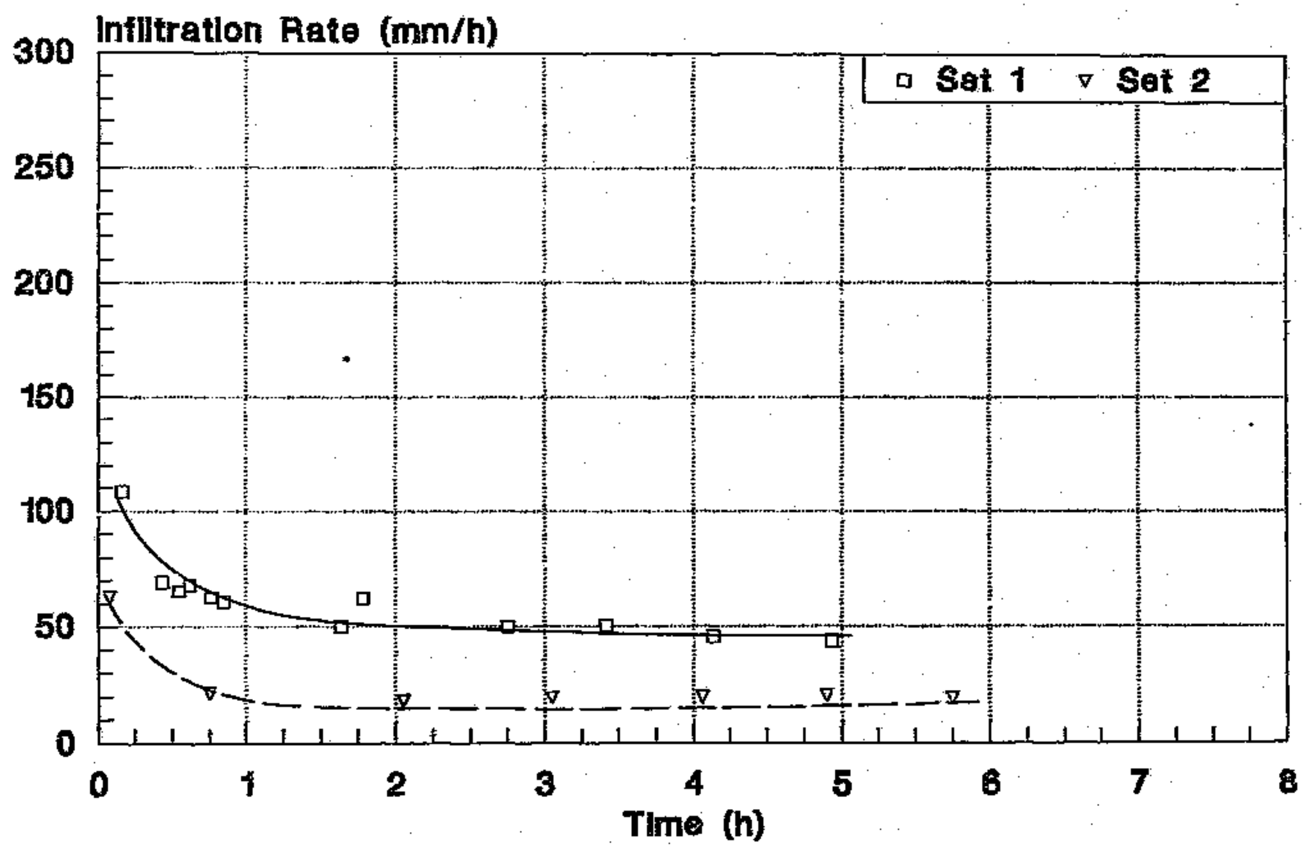
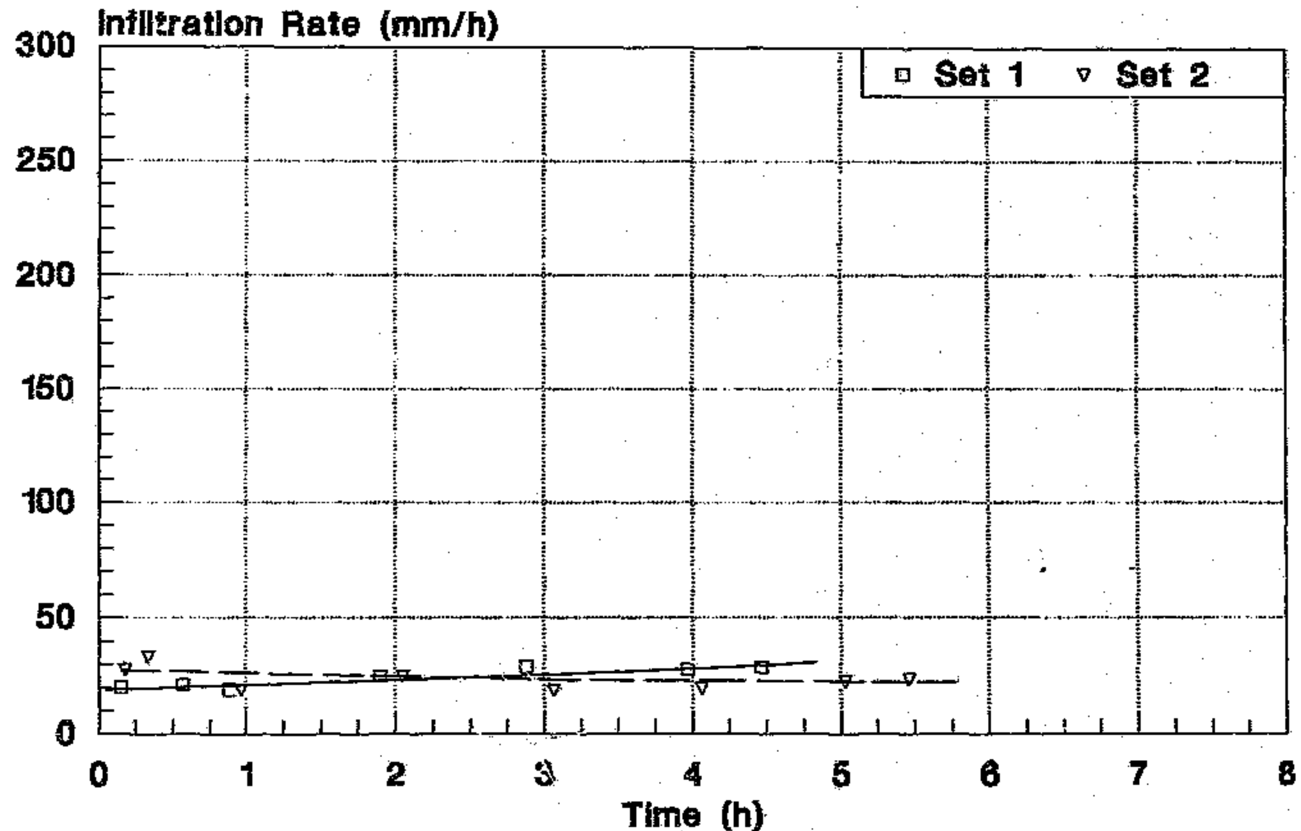


Figure F2
Infiltration During the Later Stages of
The Double Ring Infiltrometer Model Test



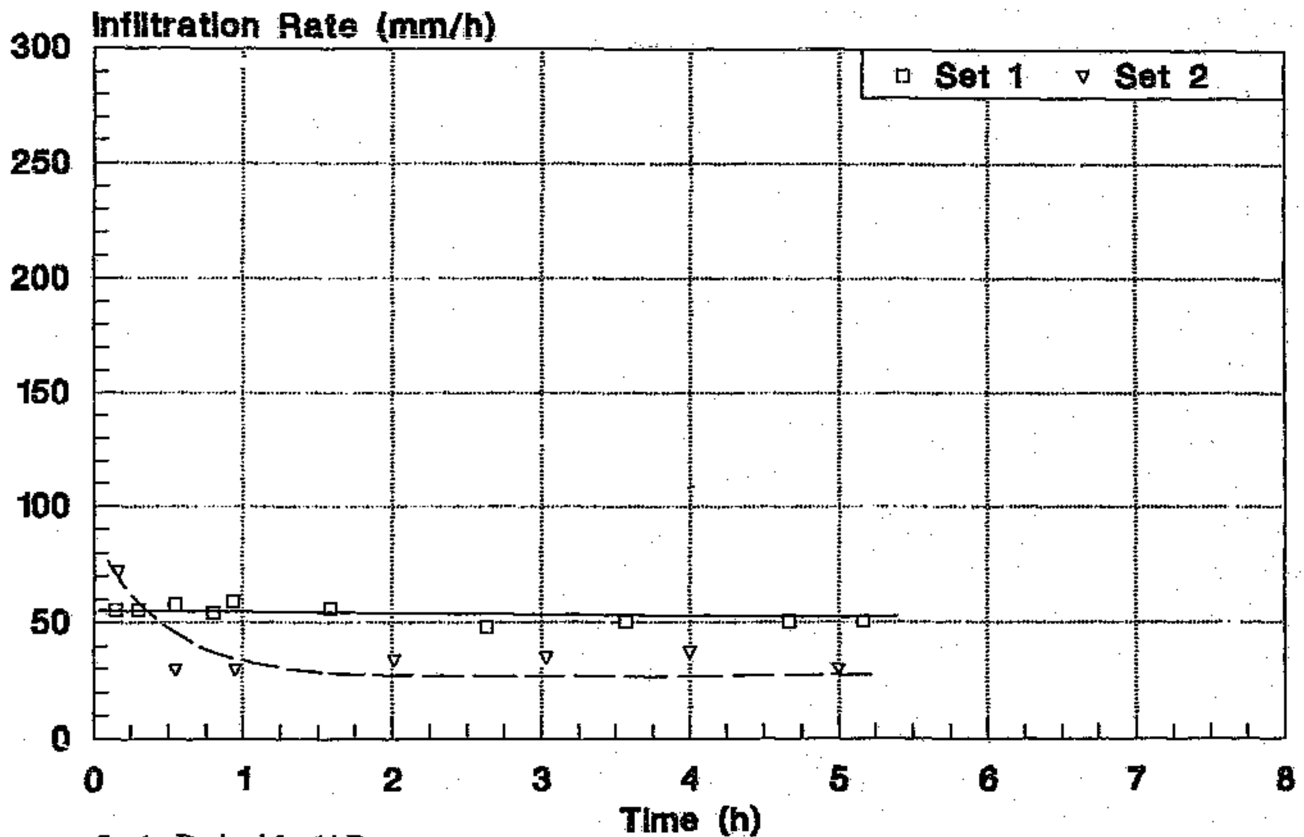
Set 1 - Natural Moisture Content (2%)
Set 2 - Drained Overnight

Figure F3
Cumulative Infiltration Rates Measured on Linbro Park Landfill, Using Distilled Water - Site 1



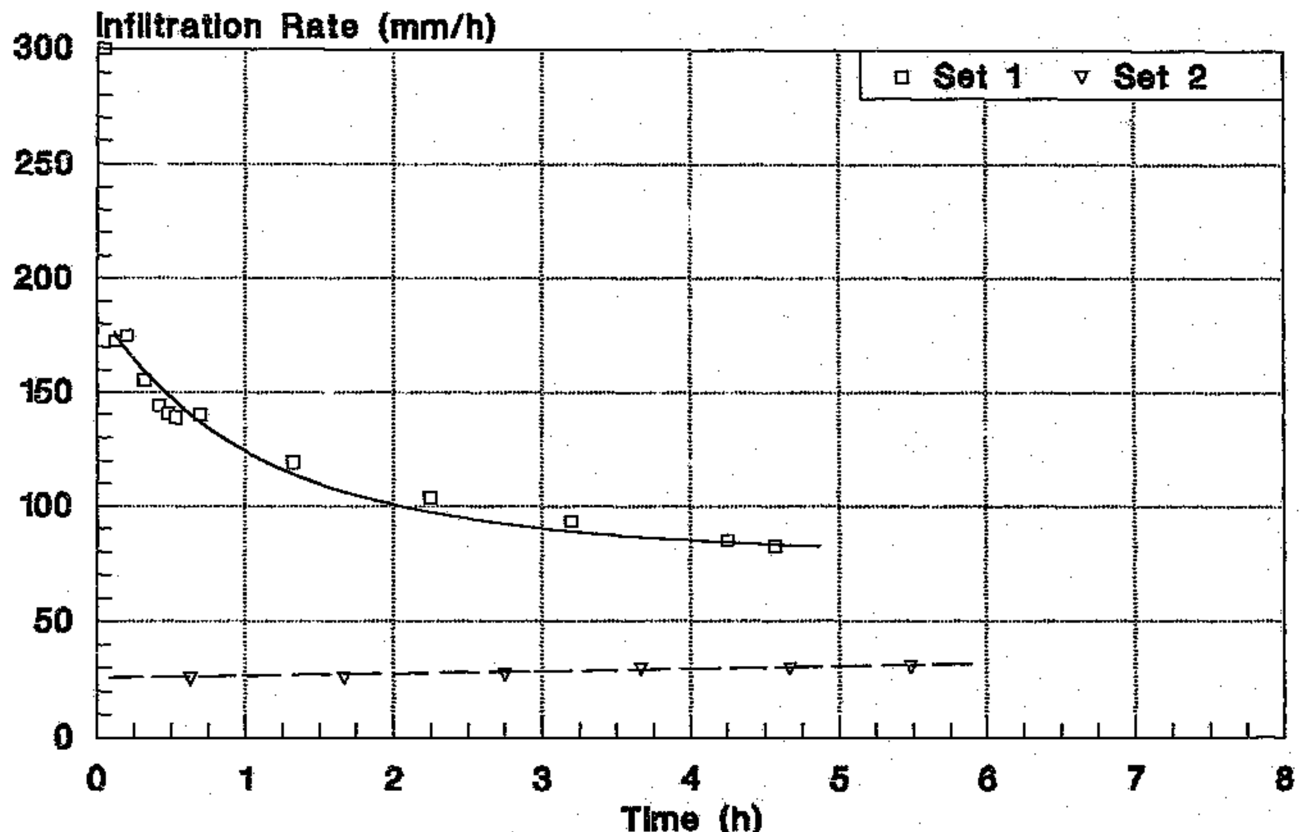
Set 1 - Drained for 14 Days
Set 2 - Drained Overnight

Figure F4
Cumulative Infiltration Rates Measured on Linbro Park Landfill, Using Rand Water Board Water - Site 1



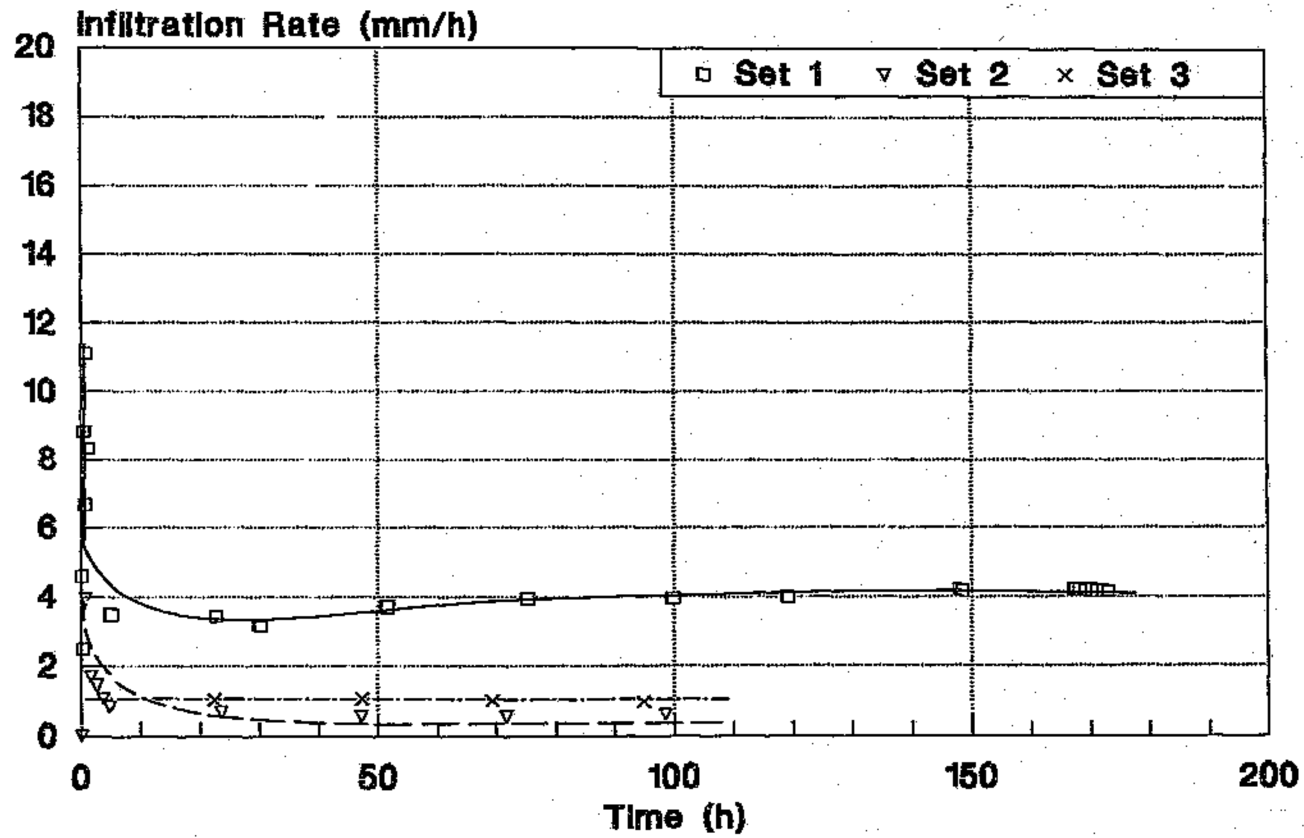
Set 1 - Drained for 14 Days
Set 2 - Drained Overnight

Figure F5
Cumulative Infiltration Rates Measured on Linbro Park Landfill, Using Distilled Water - Site 2



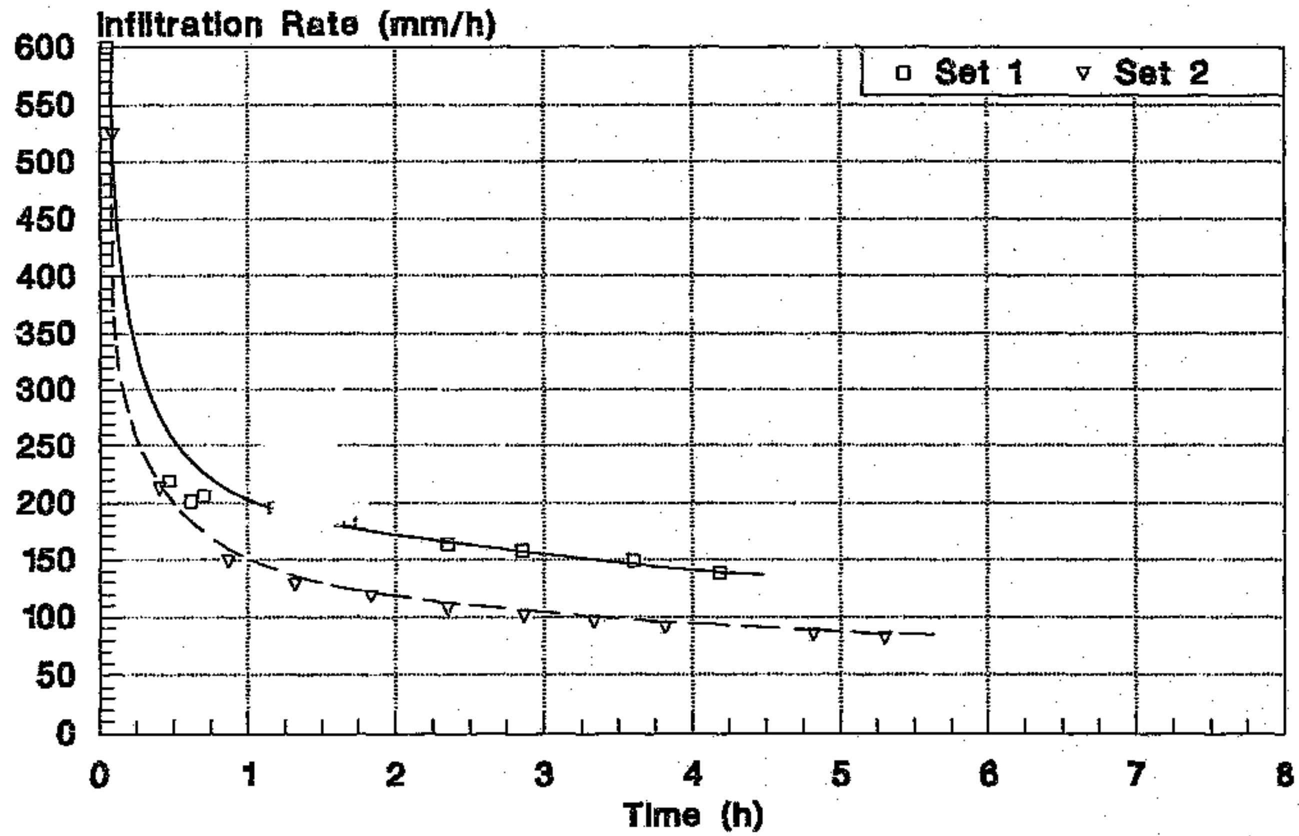
Set 1 - Natural Moisture Content (2%)
Set 2 - Drained Overnight

Figure F6
Cumulative Infiltration Rates Measured on Linbro Park Landfill, Using Rand Water Board Water - Site 2



Set 1 - Natural Moisture Content (2%); Rand Water Board Water
Set 2 - Natural Moisture Content (2%); Rand Water Board Water
Set 3 - Drained Overnight; Distilled Water

Figure F7
Cumulative Infiltration Rates Measured on Linbro Park Landfill - Site 3



Set 1 - Natural Moisture Content (2%)
Set 2 - Drained Overnight

Figure F8
Cumulative Infiltration Rates Measured on Linbro Park Landfill, Using Rand Water Board Water - Site 4

APPENDIX G

SIMULATED RAINFALL INTENSITY-DEPTH DISTRIBUTIONS

Rainfall intensity distributions, calculated from the SCS method, (as modified for South African conditions) for storm depths of 5 mm, 10 mm, and 20 mm are shown in Figures G1, G2, and G3 respectively. Superimposed on these distributions are the stepped 'rainfall' intensity distributions used in the sprinkler infiltrometer tests. Tables G1, G2, and G3 give the combinations of sprinkler spacings, nozzles, flow rates, and pressures used in the rainfall simulations.

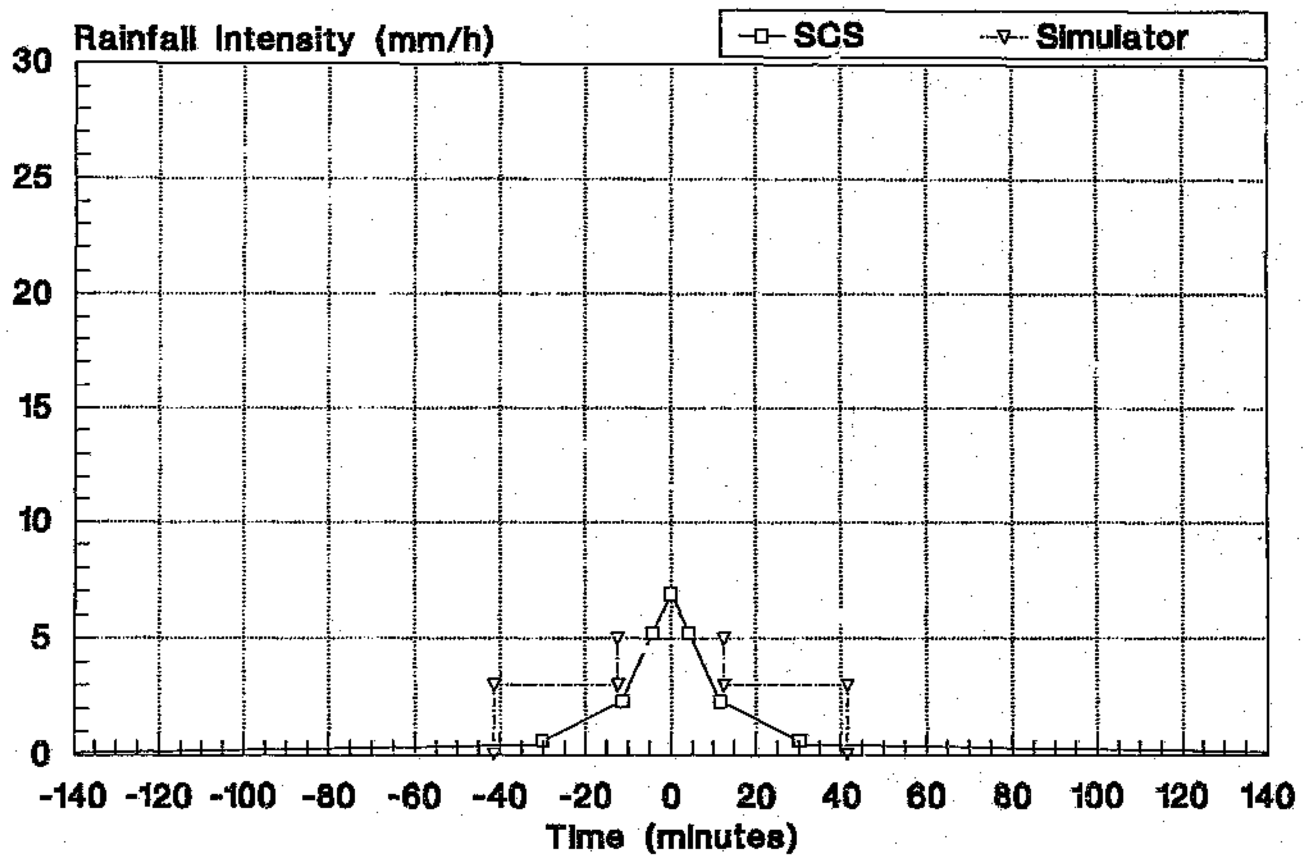


Figure G1
ainfall Intensity Dis··ibutions for SCS method, and for Sprikler Infiltrometer, for 5mm rainfall depth

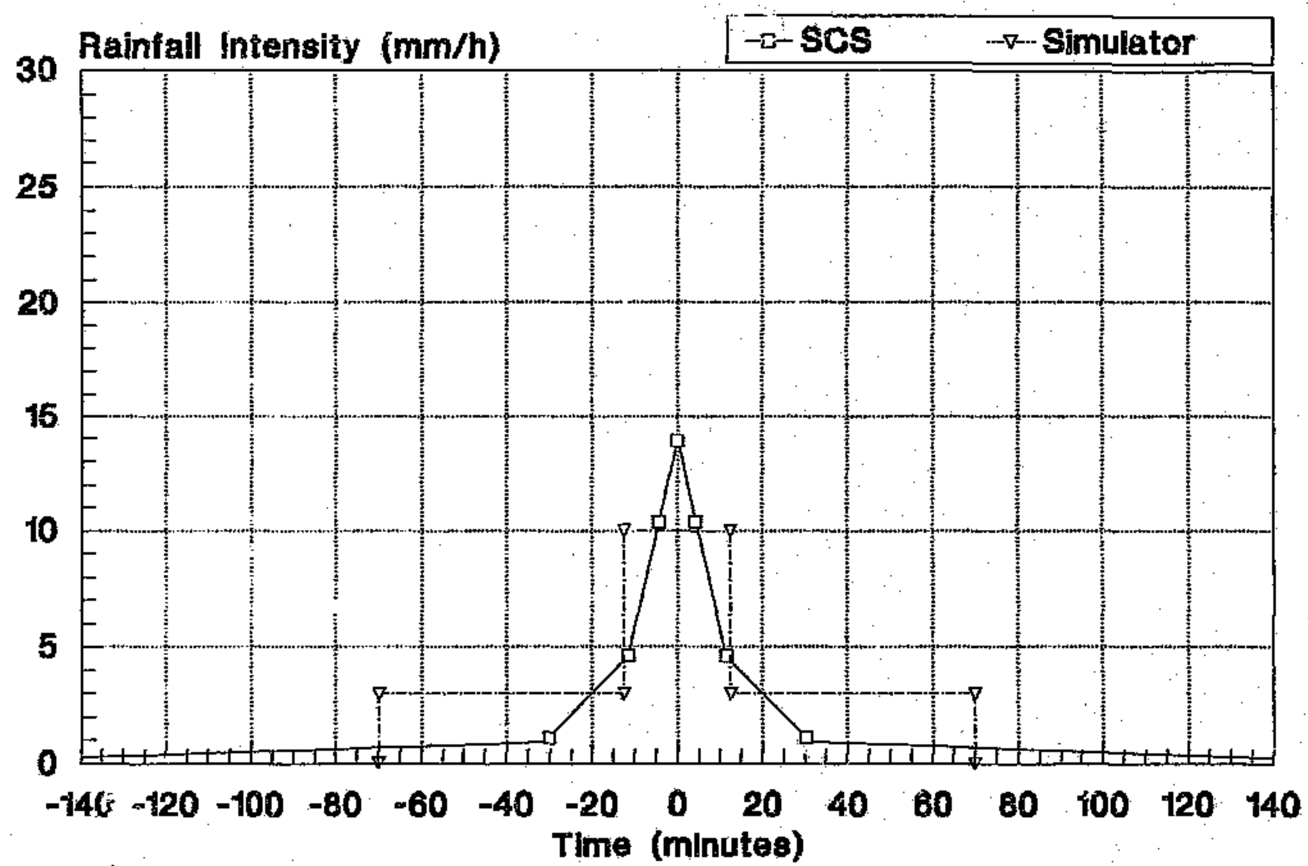


Figure G2
Rainfall Intensity Distributions for SCS method, and for Sprikler Infiltrometer, for 10mm rainfall depth

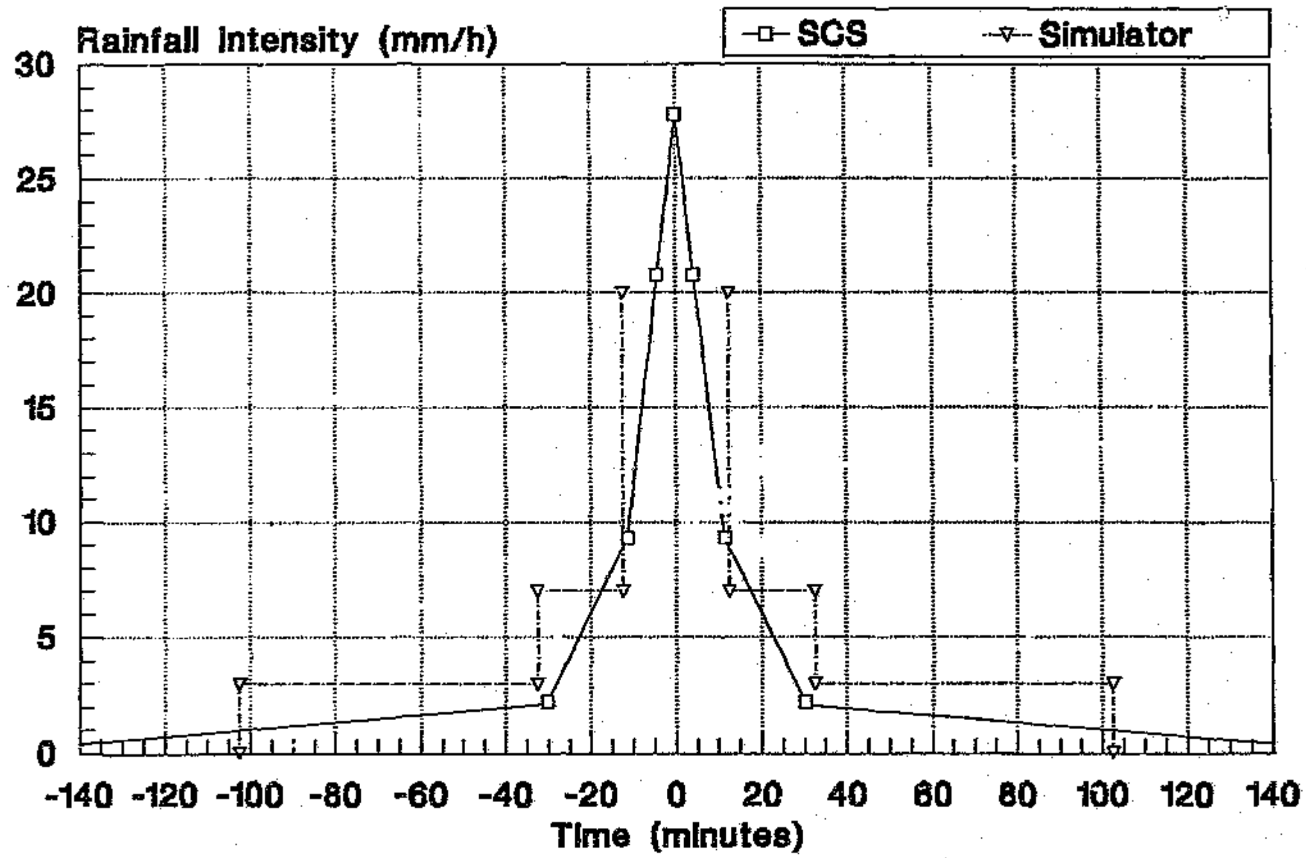


Figure G3
Rainfall Intensity Distributions for SCS method, and for Sprikler Infiltrometer, for 20mm rainfall depth

	Stage 1	Stage 2	Stage 3
Duration	30 minutes	25 minutes	30 minutes
Intensity	3 mm/h	5 mm/h	3 mm/h
Main Nozzle	1/8 inch	11/64 inch	1/8 inch
Spreader Nozzle	3/32 inch	3/32 inch	3/32 inch
Flow Rate	3.8 m^3/h	6.5 m^3/h	3.8 m^3/h
Pressure	250 kPa	300 kPa	250 kPa
Spacing	18 m x 18 m	18 m x 18 m	18 m x 18 m
Volume of Water	1.9 m^3	2.7 m^3	1.9 m^3

Table G1

Spacings, Flow Rates, Pressures, and Nozzles used for 5 mm deep Rainfall Simulation

	Stage 1	Stage 2	Stage 3
Duration	60 minutes	25 minutes	60 minutes
Intensity	3 mm/h	10 mm/h	3 mm/h
Main Nozzle	1/8 inch	11/64 inch	1/8 inch
Spreader Nozzle	3/32 inch	3/32 inch	3/32 inch
Flow Rate	3.8 m^3/h	6.5 m^3/h	3.8 m^3/h
Pressure	250 kPa	300 kPa	250 kPa
Spacing	18 m x 18 m	9 m x 18 m	18 m x 18 m
Volume of Water	3.8 m^3	2.7 m^3	3.8 m^3

Table G2

Spacings, Flow Rates, Pressures, and Nozzles used for 10 mm deep Rainfall Simulation

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Duration	70 minutes	20 minutes	25 minutes	20 minutes	70 minutes
Intensity	3 mm/h	7 mm/h	20 mm/h	7 mm/h	3mm/h
Main Nozzle	1/8 inch	11/64 inch	11/64 inch	11/64 inch	1/8 inch
Spreader Nozzle	3/32 inch	3/32 inch	3/32 inch	3/32 inch	3/32 inch
Flow Rate	3.8 m^3/h	6.5 m^3/h	6.5 m^3/h	6.5 m^3/h	3.8 m^3/h
Pressure	250 kPa	300 kPa	300 kPa	300 kPa	250 kPa
Spacing	18m x 18m	15m x 15m	9m x 9m	15m x 15m	18m x 18m
Volume of Water	4.5 m^3	2.2 m^3	2.7 m^3	2.2 m^3	4.5 m^3

Table G3

Spacings, Flow Rates, Pressures, and Nozzles used for 20 mm deep Rainfall Simulation

APPENDIX H

EXAMPLE OF SPRINKLER TEST RESULTS

An example of the results of irrigation tests, published by the South African Department of Agriculture, is shown in figure H1. The effect of using different spacings, flow rates and pressures is indicated.

Figures H2 and H3, give a graphical representation of the distribution of irrigation achieved by particular sprinkler, nozzle, flow rate, pressure, and spacing combinations. The distributions shown correspond to applications of coefficients of uniformity of 84 % and 95 % respectively.

SPRINKELAAR / SPRINKLER: SALEM 430/1770
TUIT / NOZZLE: Hoof Swart (5 mm) + sekondêre tuit (4 mm)
Main Black (5 mm) + spreader nozzle (4 mm)

TABEL MET CU WAARDES VIR WINDSTIL TOESTANDE
TABLE WITH CU VALUES FOR NO WIND CONDITIONS

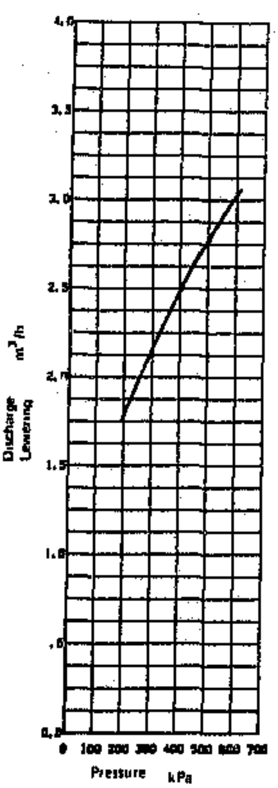
Druk Pressure (kPa)	Lewering Discharge (m³/h)	Straal Radius (m)	Spasiëring / Spacing (m)																		
			SS	9				12					15				18			21		24
			SL	9	12	15	18	12	15	18	21	24	15	18	21	24	18	21	24	21	24	24
300	2,160	15.3	mm/h	26.7	20.0	16.0	13.3	15.0	12.0	10.0	08.6	07.5	08.6	08.0	06.9	06.0	06.7	05.7	05.0	04.9	04.3	03.8
			△	90	87	88	84	89	85	80	84	82	87	82	85	81	75	75	71	73	71	77
			□	92	92	87	81	87	88	82	81	82	85	78	84	85	77	80	75	78	73	73
400	2,480	16.3	mm/h	30.6	23.0	18.4	15.3	17.2	13.8	11.5	09.8	08.6	11.0	09.2	07.9	06.9	07.7	06.6	05.7	05.6	04.9	04.3
			△	89	95	89	84	85	83	79	80	77	85	83	83	79	76	74	70	70	68	70
			□	92	88	89	81	81	87	82	77	77	86	77	80	83	75	79	75	77	71	69
500	2,760	15.3	mm/h	34.1	25.6	20.4	17.0	19.2	15.3	12.8	11.0	09.6	12.3	10.2	08.8	07.7	06.5	07.3	06.4	06.3	05.5	04.8
			△	95	96	89	88	93	87	86	91	86	87	85	85	81	80	79	78	82	83	84
			□	97	94	86	88	95	89	87	90	86	84	85	88	82	66	84	77	81	79	78

Druk = Sprinkelaarbasisdruk
Pressure = Sprinkler Base Pressure

SS = Sprinkelaarspasiëring op lateraal
= Sprinkler spacing on lateral
SL = Lateraalspasiëring
= Spacing of laterals

Steenpyp Hoogte = 1 m
Height of Riser = 1 m

GRAPH OF DISCHARGE VS PRESSURE
GRAFIEK VAN LEWERING TEEN DRUK



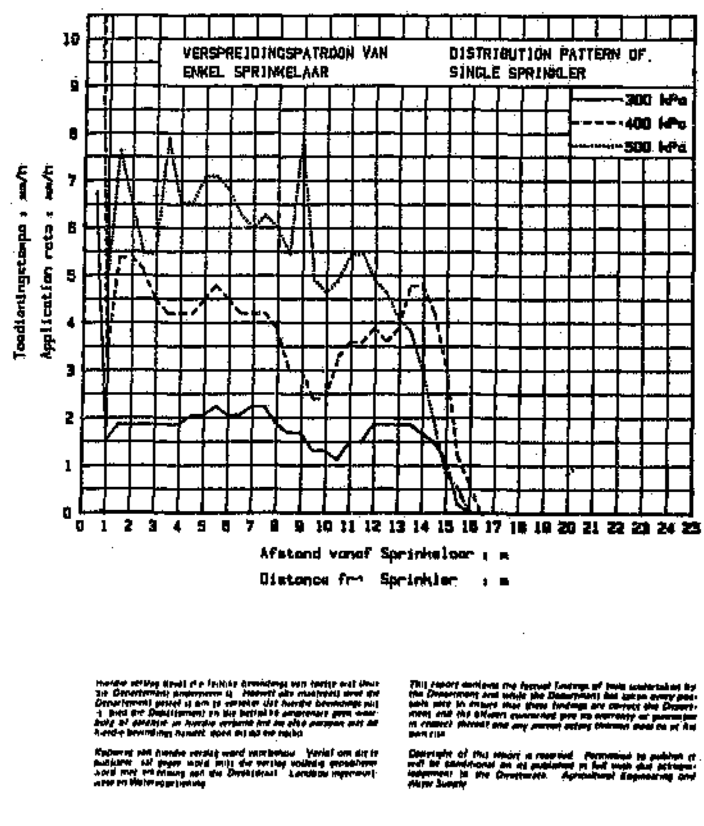


Figure H1

Example of Sprinkler Test Results (Published by South African Department of Agriculture, Directorate: Agricultural Engineering and Water Supply.)

salen 5mm 4mm

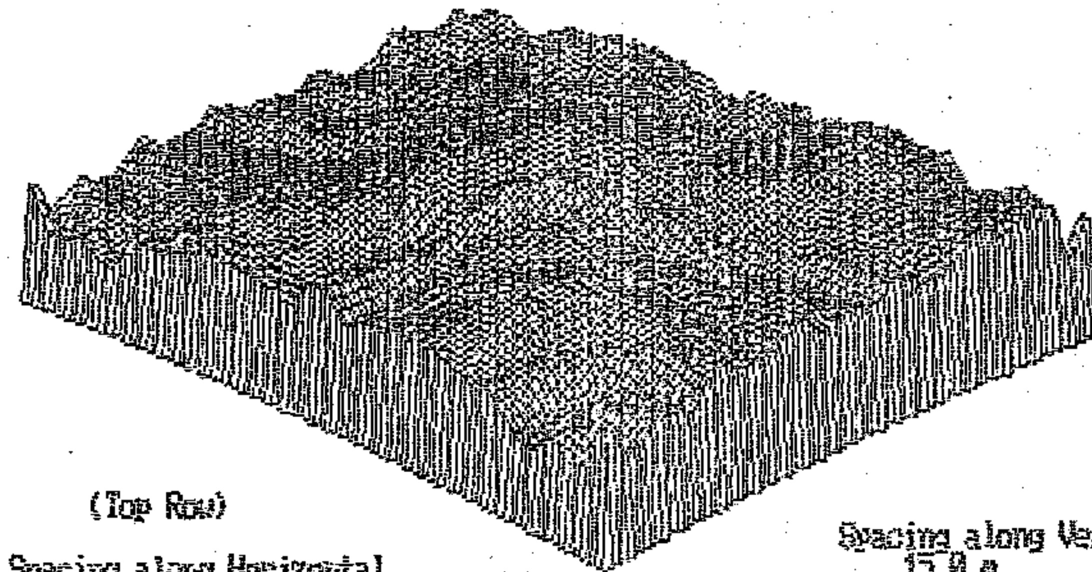


Figure H2
Graphical Representation of Distribution of Irrigation
(Sprinklers spaced at 18 m x 15 m to give average application of 10 mm/h, coefficient of uniformity of 84%)

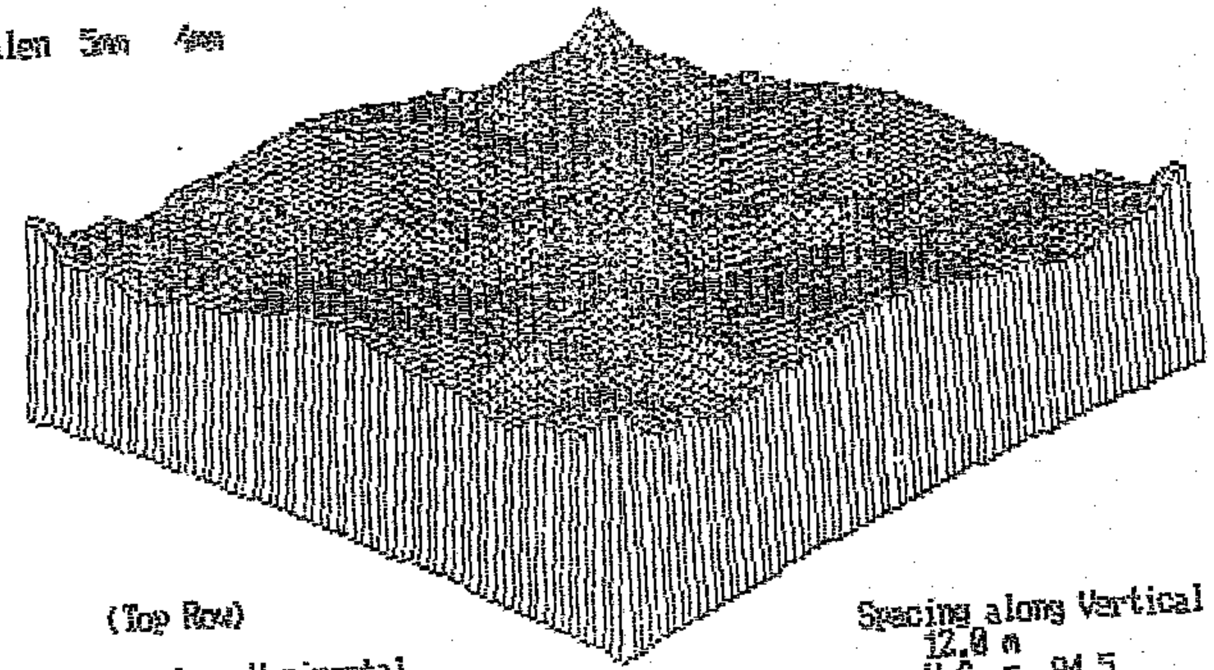


Figure H3
Graphical Representation of Distribution of Irrigation
(Sprinklers spaced at 12 m x 12 m to give average application of 19 mm/h, with coefficient of uniformity of 95%)

APPENDIX J

PUMP PERFORMANCE CURVE

The pump performance curve for the portable pump used in the sprinkler infiltrometer tests is shown in figure J1. The curve shown is supplied by the manufacturer.

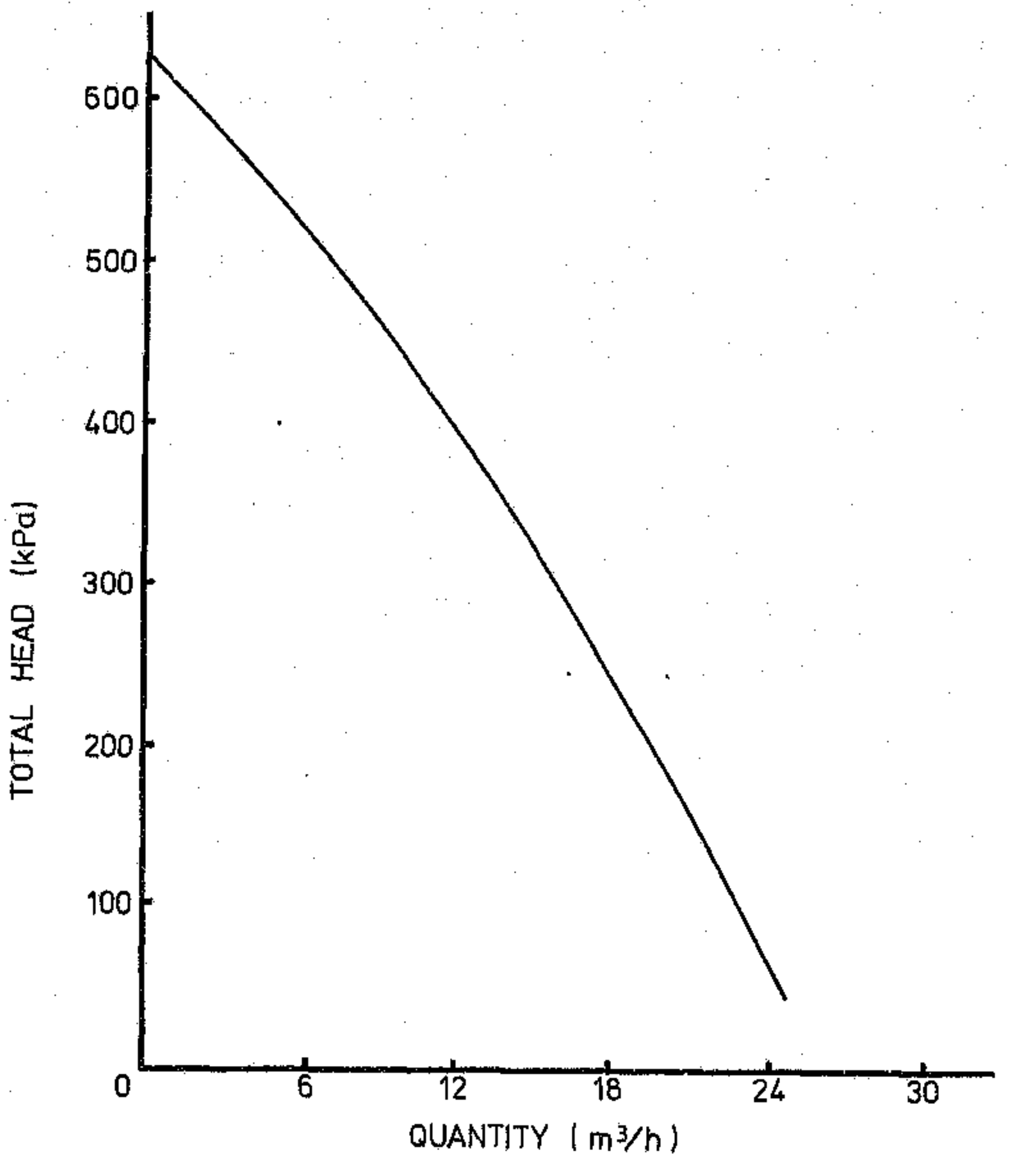


Figure J1
Pump Performance Curve for Pump used in Rain Simulations
(Pump SCH 4070; Robin EY20 motor)

APPENDIX K

RESULTS OF SPRINKLER INFILTROMETER TESTS

The results of the sprinkler infiltrometer tests are shown in tables K1, K2, and K3. The results have been summarised and discussed in Chapter 10. It should be noted that the application rates shown in the tables, are based on the measurements of the rain gauges. Water was pumped at a rate designed to yield application rates 25% to 30% higher than was recorded by the rain gauges. Evaporative losses result in lower 'effective' irrigation rates.

Plot 1 Slope = 1.7% Degree of vegetation: 75%

Storm 1 w(i) = 1.5%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	.00	
0	0	2.1	.00	.00
.25	.53	2.1	.00	.00
.5	1.05	2.1	.00	.00
.5	1.05	3.5	.00	.00
.92	2.52	3.5	.00	.00
.92	2.52	2.1	.00	.00
1.17	3.05	2.1	.00	.00
1.42	3.57	2.1	.00	.00
1.42	3.57	.0	.00	.00

Runoff = 0%

Storm 1 w(i) = 14%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	.00	.00
0	0	2.1	.00	.00
.25	.53	2.1	.00	.00
.5	1.05	2.1	.00	.00
.5	1.05	3.5		.08
.75	1.93	3.5	.02	.08
.92	2.52	3.5	.03	.06
.92	2.52	2.1		.06
1.05	2.79	2.1	.04	.31
1.42	3.57	2.1	.06	.05
1.42	3.57	.0	.06	.00

Runoff = 1.7%

Storm 2 w(i) = 2%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	.00
0	0	2.1	0	.00
.25	.53	2.1	0	.00
.5	1.05	2.1	0	.00
.75	1.58	2.1	0	.00
1	2.1	2.1	0	.00
1	2.1	7.0		.02
1.42	5.02	7.0		.02
1.67	5.54	2.1		.02
1.92	6.07	2.1		.02
2.17	6.59	2.1		.02
2.25	6.76	2.1	.03	.024
2.42	7.12	2.1	.03	.00

Runoff = .4%

Storm 3 w(i) = 2.5 %

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	.00
0	0	2.1	0	.00
.25	.53	2.1	0	.00
.5	1.05	2.1	0	.00
.75	1.58	2.1	0	.00
1	2.1	2.1	0	.00
1.17	2.46	2.1	0	.00
1.17	2.46	4.9	0	.00
1.33	3.24	4.9		.21
1.5	4.07	4.9		.21
1.5	4.07	14.0		.21
1.67	6.45	[illegible]		.21
1.92	9.95	14.0		.21
1.92	9.95	4.9		.21
2.08	10.74	4.9		.21
2.25	11.57	4.9		.21
2.25	11.57	2.1		.21
2.28	11.63	2.1	.23	.21
2.38	11.84	2.1	.25	.20
2.4	11.89	2.1	.26	.50
2.42	11.93	2.1	.28	1.00
2.52	12.14	2.1	.3	.20
2.6	12.31	2.1	.31	.13
2.73	12.58	2.1	.32	.08
2.92	12.98	2.1	.33	.05
3.22	13.61	2.1	.33	.00
3.42	14.03	2.1	.35	.10
3.42	14.03	2.1	.35	.00

Runoff = 2.5%

Table K1
Results of Sprinkler Infiltrometer Tests - Plot 1

Plot 2 Slope = 1.6% Degree of vegetation: 50%

Storm 1 w(i) = 2%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	.00	
0	0	2.1	.00	.00
.25	.53	2.1	.00	.00
.5	1.05	2.1	.00	.00
.5	1.05	3.5	.00	.00
.92	2.52	3.5	.00	.00
.92	2.52	2.1	.00	.00
1.17	3.05	2.1	.00	.00
1.42	3.57	2.1	.00	.00
1.42	3.57	.0	.00	.00

% Runoff = 0

Storm 2 w(i) = 2%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	.00
0	0	2.1	0	.00
.25	.53	2.1	0	.00
.5	1.05	2.1	0	.00
.75	1.58	2.1	0	.00
1	2.1	2.1	0	.00
1	2.1	7.0	0	.01
1.42	5.02	7.0		.01
1.43	5.02	2.1		.01
1.67	5.54	2.1	.01	.01
1.92	6.07	2.1		.01
2.17	6.59	2.1		.01
2.25	6.76	2.1		.01
2.42	7.12	2.1	.02	.01
2.42	7.12	.0	.02	.00

Runoff = .3%

Storm 3 w(i) = 2.5%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	
0	0	.0	0	ERROR
.25	.56	2.2	0	.00
.5	1.13	2.3	0	.00
.75	1.69	2.2	0	.00
1	2.25	2.2	0	.00
1.17	2.63	2.2	0	.00
1.17	2.63	5.3	0	.22
1.33	3.47	5.3	0	.22
1.5	4.37	5.3	0	.22
1.5	4.37	8.2	0	.22
1.67	5.77	8.2	0	.22
1.83	7.09	8.3	0	.22
1.83	7.09	15.0	0	.22
2	9.64	15.0	0	.22
2.17	12.19	15.0	.22	.22
2.18	12.34	15.0	.23	1.00
2.2	12.64	15.0	.26	1.50
2.22	12.94	15.0	.28	1.00
2.23	13.09	15.0	.29	1.00
2.25	13.39	15.0	.33	2.00
2.25	13.39	2.3	.33	2.00
2.27	13.43	2.3	.35	1.00
2.28	13.46	2.3	.39	4.00
2.3	13.5	2.0	.42	1.50
2.32	13.55	2.3	.46	2.00
2.33	13.57	2.3	.49	3.00
2.35	13.61	2.3	.53	2.00
2.37	13.66	2.3	.57	2.00
2.38	13.68	2.3	.61	4.00
2.4	13.73	2.3	.64	1.50
2.42	13.77	2.3	.66	1.00
2.43	13.79	2.3	.68	2.00
2.45	13.84	2.3	.69	.50
2.47	13.88	2.3	.7	.50
2.48	13.91	2.3	.7	.00
2.5	13.95	2.3	.71	.50
2.52	14	2.3	.71	.00
2.68	14.36	2.3	.73	.13
2.88	14.81	2.3	.74	.05
3.15	15.41	2.3	.74	
3.42	16.02	2.3	.75	.02
3.42	16.02	.0	.75	.00

Runoff = 4.7%

Table K2

Results of Sprinkler Infiltrometer Tests - Plot 2

Plot 3 | Slope = 20.2% | Degree of vegetation: Burnt

Storm 1 w(i) = 1%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	.00	
0	0	2.1	.00	.00
.25	.53	2.1	.00	.00
.5	1.05	2.1	.00	.00
.5	1.05	3.5	.00	.00
.92	2.52	3.5	.00	.00
.92	2.52	2.1	.00	.00
1.17	3.05	2.1	.00	.00
1.42	3.57	2.1	.00	.00
1.42	3.57	.0	.00	.00

% Runoff = 0

Storm 2 w(i) = 1%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	.00
0	0	2.1	0	.00
.25	.53	2.1	0	.00
.5	1.05	2.1	0	.00
.75	1.58	2.1	0	.00
1	2.1	2.1	0	.00
1	2.1	7.0		.04
1.42	5.02	7.0		.04
1.42	5.02	2.1		.04
1.5	5.19	2.1	.02	.04
1.67	5.54	2.1		.01
1.87	5.96	2.1		.01
1.92	6.67	2.2		.01
2.17	6.59	2.1		.01
2.42	7.12	2.1	.03	.01
2.42	7.12	.0	.03	

Runoff = .4%

Storm 3 w(i) = 2.3%

Time (hrs)	Rainfall Depth (mm)	Rainfall Rate (mm/h)	Runoff Depth (mm)	Runoff Rate (mm/h)
0	0	.0	0	.00
0	0	2.7	0	.00
.25	.68	2.7	0	.00
.5	1.35	2.7	0	.00
.75	2.03	2.7	0	.00
1	2.7	2.7	0	.00
1.17	3.16	2.7	0	.00
1.17	3.16	6.3		.03
1.33	4.17	6.3		.03
1.5	5.24	6.3		.03
1.5	5.24	18.0		.03
1.53	5.78	18.0	.01	.03
1.67	8.3	18.0		.11
1.92	12.8	18.0		.11
1.92	12.8	6.3		.11
2	13.3	6.3	.06	.11
2.25	14.88	6.3		.15
2.25	14.88	2.7		.15
2.33	15.09	2.7	.11	.15
2.5	15.55	2.7		.03
2.75	16.23	2.7		.03
3	16.9	2.7		.03
3.2	17.44	2.7	.14	.03
3.38	17.92	2.7	.15	.06
3.42	18.04	2.7	.15	.00
3.42	18.04	.0	.15	.00

Runoff = .8%

Table K3
Results of Sprinkler Infiltrometer Tests - Plot 3

APPENDIX L

STRATIGRAPHIC PRC.FILES OF SUCTION MONITORING HOLES

The profiles of the holes used to monitor suction in the cover and upper refuse layers of Linbro Park landfill are shown in figures L1 to L4. The positions of the psychrometers are also indicated.

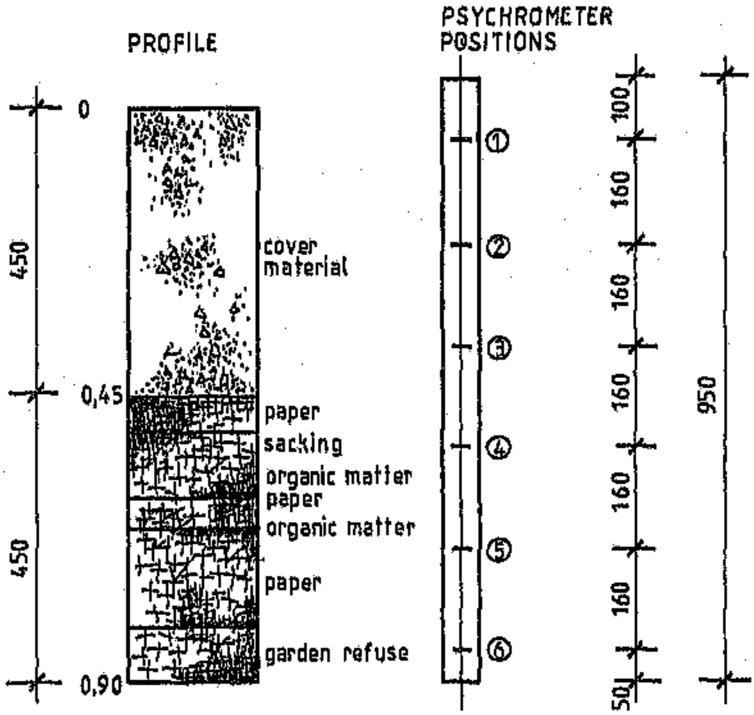


Figure L1
Sratigraphic Profile of Suction Monitoring Hole - Plot 1

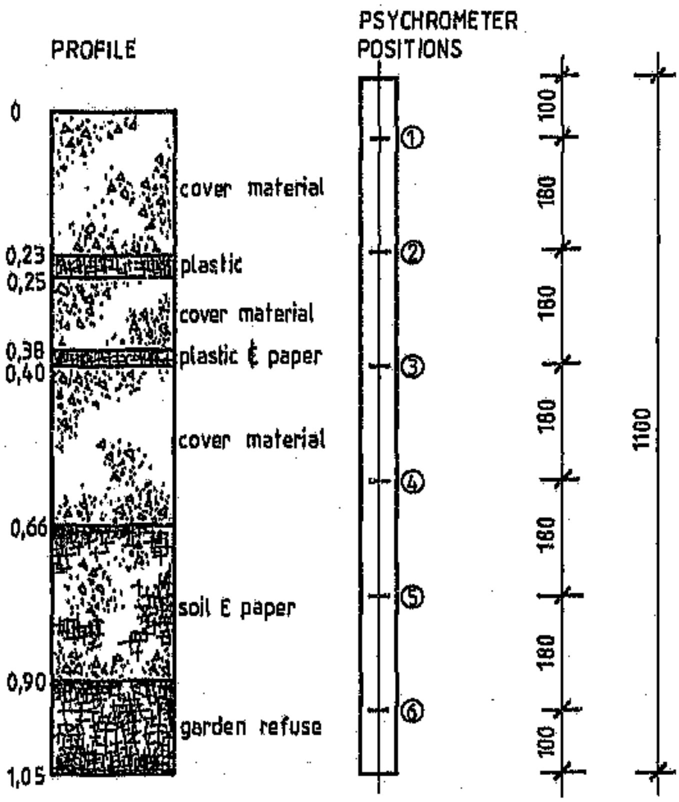


Figure I.2
Stratigraphic Profile of Suction Monitoring Hole - Plot 2

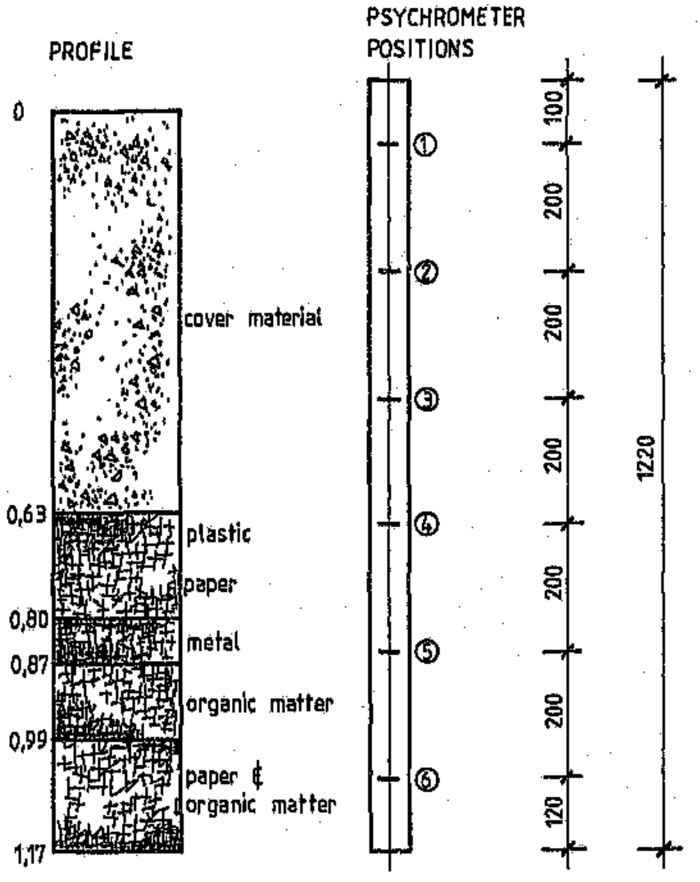


Figure L3
Stratigraphic Profile of Suction Monitoring Hole - Plot 3

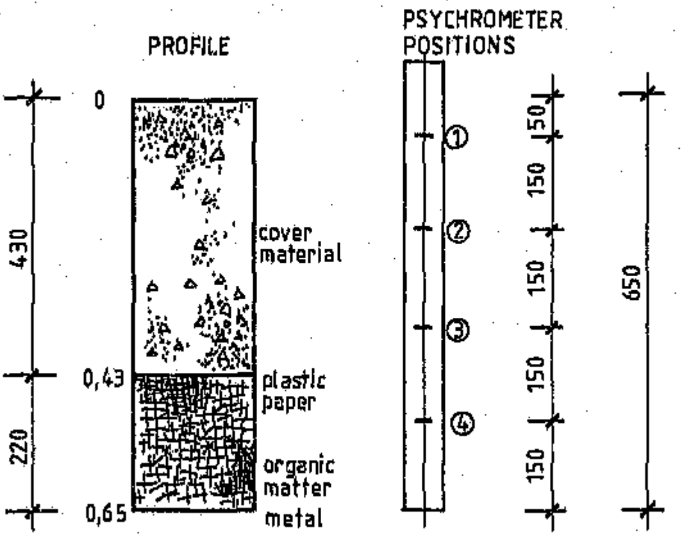


Figure L4
Stratigraphic Profile of Suction Monitoring Hole - 'Control' Plot

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