WATER BALANCE AND THE MIGRATION OF LEACHATE INTO THE UNSATURATED ZONE BENEATH A SANITARY LANDFILL

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this dissertation is my own unaided work except where indicated in the body of the report. 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.

30TH day of DECEMBER 1988.

ABSTRACT

The movement of water through refuse in a sanitary landfill produces a highly toxic by-product called leachate. The water balance, the soil cover properties and thickness, the ability of the refuse to retain water, and the attenuation properties of the soil liner all affect the production and quality of leachate.

Meteorological data has been measured and applied to various water balance formulae, profiles have been sampled and analysed *through the landfill and the unsaturated zone and compared* to the developed theory. Finally two lined test cells have been constructed on site to compare actual conditions to predictions.

Results show a large uncertainty in accurately estimating leachate production, but guidelines are given for reducing the uncertainty. They indicate that there is not a downward percolation of water at Linbro Park and that moisture movement within a landfill is seasonal.

ACKNOWLEDGEMENTS

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D.J. Hojem

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1. INTRODUCTION

1.1 The Problem under consideration :

For centuries man has disposed of his unwanted waste by dumping it somewhere out of the way, throwing it in the river or sea, or burying it. As man became more civilized and technologically advanced, waste streams increased and the problem of disposing that waste grew. People have attempted to use the waste beneficially by landscaping, filling unsightly excavations and pits, or reclaiming wetlands. As little as 30 years ago schools and sports clubs were requesting the Johannesburg City Council to fill areas with household refuse for use as sports fields. In fact some of the City's finest golf courses and sports fields have been laid out over refuse fill.

In the 1960's and 70's environmental awareness became a key issue in first world countries. Problems of waste disposal came under scrutiny and researchers discovered that even the local household refuse "dump" could be a potent source of groundwater pollution. A highly contaminated liquid known as "leachate" is formed by the passage of water through wastes, extracting pollutants by means of physical, chemical and biological processes. This leachate may eventually emerge from the base of the landfill in concentrations which can be up to 200 times more potent than raw sewage [1].

This report investigates the various interactions that allow water access to the wastes, the rate of flow through the wastes and percolation into the unsaturated zone beneath the landfill. It is considered that at least 95% of South Africa's wastes are presently deposited on landfills and unless the cost of operating a landfill rises exponentially this situation is unlikely to change. It is thus important that there be an understanding of how leachate is generated, in what quantities and how to control it.

1.2 Definition of some fundamental terms :

Urban Wastes - originate from domestic activities, trading, industrial operations and littering (Malan (25)). For the purposes of this report urban waste does not include sewage and does not include any hazardous waste.

Sanitary Landfill - as defined by the USA Environmental Protection Agency. *An engineered method of disposing* wastes on land in a manner that protects the environment, by spreading the waste in thin layers, compacting it to the smallest practicable volume and covering it with soil at the end of each working day (3).

Leachate - is formed when water passes through decomposing refuse. It is defined as a highly contaminated, aqueous solution which carries in it dissolved solids and the final and intermediate products of decomposition (Ball [4]). The system is extremely complex containing soluble and insoluble, organic and inorganic, ionic and nonionic and bacteriological constituents.

Biogas - is the landfill gas resulting from the decomposition reaction of the refuse. Its main constituents are Carbon dioxide and Methane but at various stages in decomposition Nitrogen, Hydrogen and Oxygen are given off. Trace quantities, (up to 0,2%), of halogenated aromatics have also been detected (Rettenberger [5]).

Water balance - In any closed system the water entering into the system will balance with the water going out, plus the water retained in the system. Thus the *algebraic sum of the* climatological factors of precipitation, evapotranspiration, surface runoff, *infiltration and soil moisture storage will* balance. The water balance model is used to determine the excess *water available for leachate production in a landfill.*

Unsaturated zone - for the purposes of this report is the soil layer that lies between the base of the refuse and the water *table.*

Attenuation site - is a site which relies on the properties of the soil in the unsaturated zone to purify or "cleanse" the leachate as it percolates through. On reaching the groundwater the less contaminated leachate will then be further attenuated, diluted and dispersed.

Containment site - is a site which relies on a synthetic or natural clay liner effectively to seal the leachate from the groundwater below. For this reason leachate has to be collected and extracted from the landfill and treated elsewhere.

1.3 Preview of work undertaken

Initially a review of existing literature was undertaken to find out the status quo of waste management research in the world and particularly in South Africa. The investigation itself involved field and laboratory work. Laboratory work involved the determination of various properties of soil and [illegible] wastes, so that they could be applied to the landfill in question. The field work involved gathering meteorological data, obtaining samples of refuse and of unsaturated zone soil for analysis, and constructing test lysimeters to obtain field evidence to support or alter the theory.

The report begins with a literature review. This includes a background of the theory of water balance, landfill design philosophies, and the chemistry of leachate production.

Linbro Park, the main landfill investigated in the report, is then discussed in terms of its history and present status as regards water pollution. The philosophy behind the research is then set out in detail with a discussion of the different elements of experimentation, analysis, and the results thereof.

Finally a summary is given of the different results, conclusions are drawn, and recommendations given with reference to the design of a domestic wastes sanitary landfill.

2. LITERATURE REVIEW

To obtain a background and a platform on which to continue research, a review of existing literature on the subject of solid wastes, leachate generation and factors influencing its generation, was conducted. An attempt was made to find out the status quo of research into the field of solid wastes.

2.1 Trends in Solid Waste Management Overseas

In the UK as recently as 1970 [6] a report of the "ad hoc group on refuse disposal" stated that: "103 : Tipping refuse into water has been frowned upon until very recently because it causes the water to turn black and emit a foul odour.... . Enough experimental work has now been done to show that wet pits can be reclaimed by refuse if the work is carefully planned and supervised by a chemist ....". While it appears that this group recognised the fact that wet *tipping may produce contaminated* water they felt that "controlled" wet tipping was an acceptable practice.

The UK has since recognised the problems of contaminant migration and have developed a "Best Practicable Environmental Option" (BPEO) design philosophy (Knox [7]). This philosophy combines the best of containment and attenuation approaches depending on the different variables. The USA (8) wish to restrict water ingress to the landfill as much as possible and even aim to prohibit leachate and gas condensate recirculation. Italy (9) *prohibits landfills in so called "humid" areas* (i.e. marshes and flood plains), Austria (10), France (11) and Sweden (12) all aim to minimise water ingress to the landfill. The Danish Code (13) on the other hand states that water MUST be able to gain access to the waste to facilitate degradation and landfill stability. All the leachate must however be collected and treated thus restricting the Danish design philosophy to containment sites only.

In the past a clay or brick quarry or pit was considered an ideal location for a sanitary landfill. Austria (10) does not permit a *landfill* to be sited in any depression in the ground. Italy (9) has a similar philosophy. Heath and Lehr (14) have a more controversial outlook as they recommend attenuation as the only design philosophy, and claim that "leakproof" and "secure" containment sites are never "leak proof" and "secure".

Lagekvist of Sweden (12) has an extreme point of view in wanting to ban landfilling altogether. He sees it as a method to buy time until a final solution to the problem of waste disposal is found. He claims that the emission of landfill gas is a contributor to the greenhouse effect, depletion of the ozone *layer and* the increase of halogenated organics in the atmosphere.

The sanitary landfill has long passed the stage of being just the town dump. It is now considered to be a biochemical and microbiological reactor [15] which can be controlled by applying or changing different conditions (moisture, temperature, oxygen and catalysts). The outputs of leachate and landfill gas can be influenced and controlled to a certain extent as shown by Stegman [16], Cossu [17], Becker [13], Leuschner [18] and Willumsen [19].

Research and new developments into landfills are taking place very rapidly. Overseas research appears to be focused mainly on landfill gas, methods of enhancing gas production and sophisticated methods of treating leachate. The differing, and what sometimes appear to be opposing, codes of practice produced by different countries are all the result of years of research and logical deduction. The differences indicate the wide range of uncertainty in the field of Solid Wastes, and from that uncertainty a philosophy must be found to minimise environmental pollution of the land.

2.2 Solid Waste Management in South Africa.

"It has become quite apparent that the future of hazardous waste control is more towards reduction and avoidance than towards hazardous waste management and control" (de Bruin [20]). To avoid producing wastes would be a total, but impossible solution. The central theme to the statement however, is the reduction of wastes.

South Africa's present population is almost 36,5 million and could double within the next 30 years (Malan [2]). It has been estimated (Lawrence [21]) that by the year 2000 the urbanised population in South Africa would have risen from its present 62% to 80% of the total population. Add to this the urban population growth of 9 to 10% per annum (Verrier [22]) and one can see the rapidly expanding problem local authorities have for the disposal of urban wastes. The intended promulgation of Section 12(2)(a) of the Environmental Conservation Act (Act 100 of 1982) is a great stride towards the protection of our resources.

Hattingh [23] quotes some statistics of existing South African landfills. 47,6% showed no evidence of surface water pollution, 10,4% indicated a possibility and 38,4% displayed clear evidence. He did not quote statistics for groundwater but the problem of surface water pollution indicates immediately the sad state of South Africa's landfills. De Bruin [24] gives a summary of current waste disposal practices in South Africa which has been reproduced in table 2.1.

TABLE 2.1 NUMBERS OF LOCAL AUTHORITIES

	Cape	Natal	OFS	Tvl	Total	%
Uncontrolled	121	27	46	31	225	27,6
Landfill	126	53	40	120	339	41,6
Burning	116	7	12	35	170	20,5
Composting	21	2	0	6	31	3,8
Partial recycling	0	4	7	14	25	3,1
No service	7	3	3	12	25	3,1
	391	96	108	220	815	100

It is claimed that only 48% of these practices are environmentally acceptable. Joubert (25) states that the vast majority of municipalities give waste disposal their lowest priority *with very little finance being channelled in this direction*. A major municipality in South Africa apportions only 2% of its total services expenditure to waste management (26). The smaller local authorities have the usual problem of too few funds and thus cleansing becomes a neglected service. Ball (27) attributes some of the blame to the lack of genuine interest on the part of the management.

A design philosophy has not yet been laid out in South African codes, but the National Research Programme for Waste Management the CSIR's Foundation for Research and Development has produced a set of draft guidelines "for the effective disposal and control of waste" (28). These are closely linked to the Environmental Conservation Act. Ball and Blight (29) indicate that a South African waste disposal philosophy will draw from both containment and Attenuation philosophies depending on the *different conditions involved. For example, the water surplus* areas would concentrate more on a containment design while the water deficit areas would be better suited to attenuation. However that is not a hard and fast rule and a thorough understanding of the factors and mechanisms involved is required for a decision as to the type of design required.

2.3 Properties and behaviour or refuse

2.3.1 Refuse Composition

Of the total waste stream in South Africa, municipal solid wastes make up 6% or 18 million tons, the remainder being primarily mining wastes, and a smaller percentage of chemical and industrial wastes (26).

The actual composition of municipal waste is variable, and depends on socio economic factors, geographical situation, season, and cultural background. Attempts have been made to determine the breakdown into various component percentages as quoted in Table 2.2 below.

TABLE 2.2 : DOMESTIC WASTE COMPOSITION

CONSTITUENTS	JOHANNESBURG[1]	P.ELIZABETH[2]	CAPE TOWN[2]	SOWETO[3]
Paper	34	18	29	4
Putrescible	30	36	23	1 5
Metal	6	3	5	1
Glass	10	7	14	2
Plastic	7	3	6	1
Textile	3	1	1	1
Ash (fines)	2	5	6	4 5
Unclassified	8	5	10	3 1
Garden	-	27	6	-

1 Venter (30) 2 Lawrence (21) 3 Van Rensburg (31)

Leuschner (15) broadly classifies municipal solid wastes into 25% inorganics, 25% moisture and 50% organic matter. In refuse decomposition and the production of leachate and biogas it is this 50% organic matter that we are primarily concerned with.

2.3.2 Refuse decomposition

Decomposition occurs with all but the most inert wastes. It is a complex process involving physical, chemical and biological reactions interacting simultaneously to produce leachate, gas and altered wastes. *The physical process results from pressures* exerted on the wastes and the physical leaching of material from the waste to change its physical characteristics (such as strength). The chemical process involves redox reactions, precipitation and adsorption/desorption reactions and can take place throughout the life of the fill. The major mechanism for decomposition is however biological (Ham [32]).

The three major phases of biological decomposition are; the aerobic phase, the acid anaerobic (or facultative) phase, and the methanogenic anaerobic phase (Ham and Barlaz [33]).

Aerobic decomposition is characterised by the presence of oxygen. It is usually very rapid and produces heat (50°C to 70°C) and carbon dioxide.

The facultative or acid phase can exist with oxygen but makes use of other electron acceptors in its absence. Less heat is produced than in the aerobic phase and a large amount of organic acids are produced (smelly phase).

Methanogenic anaerobic organisms require a very low redox potential and no oxygen. Heat is maintained at acid phase levels, reactions are slow and carbon dioxide and methane are produced. The methanogenic bacteria are separated into 3 broad classifications according to the temperature range in which they thrive (Moss [11]) i.e. psychrophiles ($12^{\circ}C$ to $18^{\circ}C$), mesophiles ($25^{\circ}C$ to $40^{\circ}C$) and thermophiles ($55^{\circ}C$ to $60^{\circ}C$).

A number of experiments have been conducted to increase rates of refuse decomposition and gas generation, and to alter the composition and toxicity of leachate. Becker [16] shows conversions during acid phase degradation in Fig 2.1.

BIOPOLYMER (carbohydrate, protein, fat).

Hydrolysis ↓

MONOMER (sugar, amino acids, fatty acids)

Acidification ↓

VOLATILE FATTY ACIDS (ethanol)

Acetogenesis ↓

ACETATE, (carbon dioxide, hydrogen)

Methanogenesis ↓

METHANE + CARBON DIOXIDE

FIGURE 2.1

Becker states that the acidification phase produces the most toxic leachate and so this phase must be reduced. This can be done by:

a) Including less reactive wastes (compost sludge etc.)

b) Precomposting waste (quick decaying materials disappear as carbon dioxide into the air).

c) Decreasing volatile fatty acid concentrations by recirculation.

Leuschner (15) found that mesophilic temperatures (37°C) were optimal and that recycled leachate could be buffered to increase the pH of the fill.

Stegman and Spendlin (16) and Doedens and Landwehr (34) recommend using a precomposted bottom layer of refuse to speed up the acid phase degeneration and reduce the toxicity of the leachate.

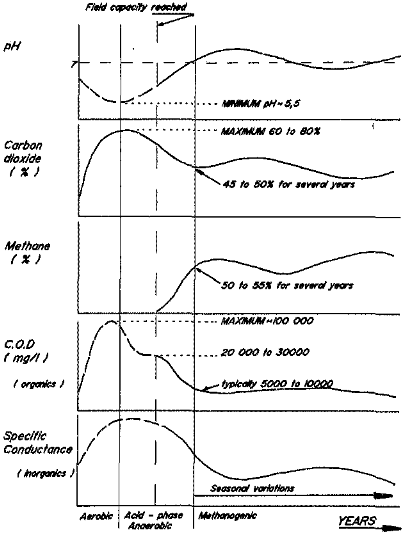
Ham (32) shows theoretical degradation curves which are reproduced in Fig 2.2.

2.3.3 Leachate

Leachate is one of the products of the decomposition process and its properties depend largely on the properties of the waste through which it has percolated. Generally speaking leachate can identify with the acid phase decomposition (low pH, high COD) or with the methanogenic phase (high pH, low COD).

The USA Environmental Protection Agency emphasise that

FIGURE 2.2 THEORETICAL DEGRADATION CURVES



Interpretation of reported leachate data must be done with extreme caution (35). Leachate composition reported in the literature is diverse. Among the factors that contribute to the variability of data are :

a) Time since deposition of the waste.
b) The moisture regimen - volume, intensity, distribution and direction of flow.
c) The waste characteristics
d) Temperature
e) Sampling and analytical measurements.

An analysis of about 63 landfills by Ham (32), Barber (36), Ehrig (37), Knox (38) and Cheremisinoff and Giglello (39) produces a "typical" averaged leachate as shown in Table 2.3.

TABLE 2.3 : "TYPICAL" LEACHATE

	ACID PHASE	METHANOGENIC PHASE
pH	5,8	8,0
COD	25600	1600
BOD_5	13000	180
Fe	715	8
Ca	1720	165
Mg	440	165
Mn	35	0,6
Zn	25	0,4
Sr	7	0.9
SO_4	995	270
NH_4 as N	500*	
NO_3 as N	3,2*	
Conductivity	7175*	
Alkalinity as $CaCO_3$	4320*	
Hardness	2590*	
Cl	2000*	
Na	1640*	
K	860*	

* Applies to both acid and methanogenic phases

Depending on the wastes there could be additional quantities of leachate constituents present, some of which could be extremely harmful. Some solvents, for example, are not degradable in the landfill and appear in the leachate in the same quantities as originally disposed. (Ham [32]).

Connell [40] refers to a branch of chemical analysis known as "ecotoxicology" which provides measures of the response of chemicals and organisms to changes in the environment. It is too vast to consider in the context of this study but we can consider the factor of mobility of pollutants in the context of leachate migration. ,tensen et al [41] summarises as follows:

a) very mobile pollutants - Cl, conductivity, total solids and COD

b) Moderately mobile - Na, NH_4 , K, Mg, Fe.

c) Partly mobile - Fe and Mn

d) Very restricted - Zn and Cd.

Fatty acids are mobile in the aerobic phase but retarded in the anaerobic phase.

Roulier [47] supports him, indicating contaminant mobility as Cl > Na > COD > Mg > NH_4 > K > Si > Fe and for metals Hg, Cr, Se > Cd, As, Zn > Cu, Pb.

Ellis [43] describes potassium (K) as a convenient parameter for tracing leachate, but according to Christensen and Roulier it may not be mobile enough.

The quantity of leachate depends on the sources of water in the landfill. This can include the inherent moisture in the refuse at placement, the water produced as a product of a chemical or microbiological reaction within the wastes, condensate from landfill gases, groundwater infiltration through the base due to a rise in the ground water table and surface water infiltration through the cap due to rainfall and run on (Naylor et al [44]).

2.4 Water Balance :

Water that infiltrates the top layer of a landfill and then percolates through the waste becomes contaminated and forms leachate. In addition to becoming a toxic by-product of the landfill, water will affect the rate of decomposition of the waste, gas emissions, and rate of settlement. It is thus important for the landfill designer and operator to know exactly where all the water that arrives at the landfill, eventually ends up.

On a Global scale the different elements of analysis for the Water Balance are well set out by Dyck [45] as shown in figure 2.3

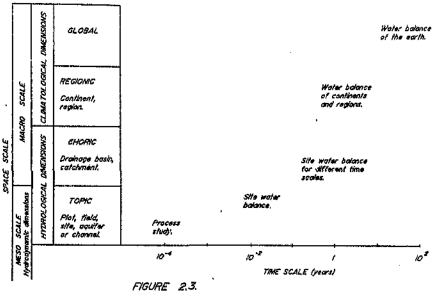


FIGURE 2.3.

In general precipitation provides the largest component of the water balance and evapotranspiration the second largest. For a site specific purpose such as sanitary landfill the Meso scale of analysis applies.

O' Leary and Tansel [46], Fenn et al [47], and Ham [32] use a simplified model where $P = R/O + ET + Perc - \Delta ST$ (eqn 2.1) and

P = precipitation

R/O = Run off

ET = evapotranspiration

Perc = percolation

ΔST = change in soil moisture storage.

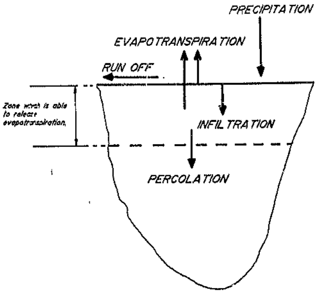


FIGURE 2.4 Simplified water balance

Baccini et al (48) used a more complicated form of the water balance equation which relates water changes specific to waste as in the equation below.

$$\underbrace{P + W}_{\text{Input}} + \underbrace{B}_{\text{Production}} - \underbrace{(E + G + L + V)}_{\text{Output}} - \underbrace{S}_{\text{Retention}} = 0$$

where P = precipitation

W = inherent water contents (due to incoming waste)

B = biochemical water production

E = evaporation

G = output by gas (i.e. water vapour).

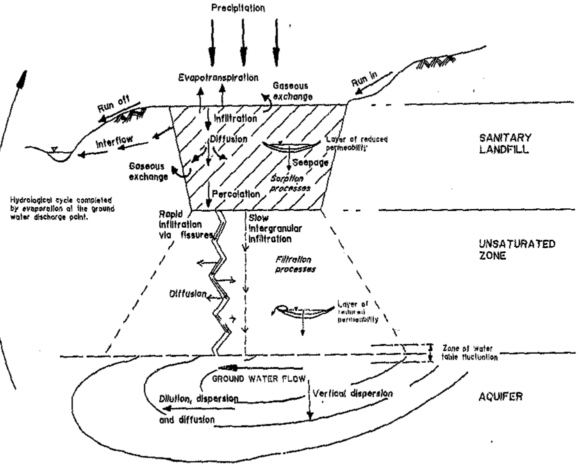


FIGURE 2.5 Detailed water balance in a sanitary *landfill*

L = leachate

V = losses due to runoff

S = retention by the waste.

all measured in g water per kg waste per year.

B can be between 0 and 20g/kg/annum depending on the biological activity at the time. G<=1,5g/kg/annum.

Naylor et al (44) has a similar equation for which the water balance is shown in Fig 2.5, and shows percolation below the base of the fill (i.e. leachate) as,

$$P_e \ (m^3/annum) = (P-E_p)\times A_{(landfill)} + R\times A_{(run\ in)} + (L_d-(E_d\times A_{(lagoon)})) + \Delta S$$

where: E_p = actual evapotranspiration

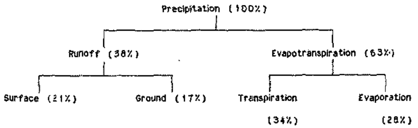
L_d = rate of liquid disposal into the landfill (m^3/a)

R = surface run in

E_d = actual evaporation from liquid disposal.

ΔS = change in moisture storage in the landfill and its cover.

Weimer (49) relates the water balance in percentages for an area where the precipitation is 720 mm/annum.



Weimer carries on to state that in Hessen, Germany, two meteorological stations situated 20 km apart, were analysed. Because of the change in topography the one station received 1100 mm of rainfall per annum, of which 55% became leachate, and the other station received 550mm of rainfall per annum, of which 6% became leachate.

Keenan (50) shows figures indicating that landfills receiving greater than 750mm of rainfall per annum will eventually produce leachate while arid regions receiving less than 325 mm are likely never to produce leachate. Saxton (51) supports Weimer and Keenan in stating that, for climates where annual rainfall is less that 400mm, virtually all precipitation returns to the atmosphere by evapotranspiration.

South Africa has widely differing microclimates, from less than 125mm annual precipitation and 3000 mm annual free water evaporation on the arid West Coast, to over 1 000 mm annual precipitation and a minimum of 1 150 mm evaporation on the East

Coast (Lund [52]). Only 10% of the land mass is likely to receive greater than 750 mm of rainfall per annum. Figure 2.6. shows the areas of water surplus and water deficit in South Africa as described by Brink [53].

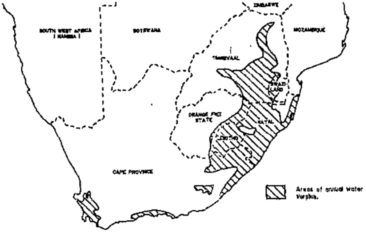


FIGURE 2.6 Water surplus areas of Southern Africa (ex. Brink [53])

It is necessary to understand the shortcomings in calculating or measuring the different elements in the water balance equation so each will be discussed separately.

2.4.1 Precipitation

Precipitation is the basic source of water and can include rain, hail, sleet and snow. This is usually the result of the condensation of atmospheric water vapour which occurs at the dew point (i.e. temperature at the point of saturation).

As an example, a relative humidity of 100% (i.e. saturation) will occur with 17,31 g water/m^3 of air at 20 ^oC, and only 4,85g water/m^3 of air at 0 ^oC. (Ref: Gray [54]).

Moisture laden air moving up a mountain slope cools by expansion and causes "orographic" precipitation. Similarly moist air near the ground surface is heated by the sun, rises by convection, cools at the higher level and causes "convective" precipitation. Inblowing winds towards areas of low barometric pressure or fronts cause "cyclonic" or "frontal" precipitation. The three precipitation mechanisms are shown in Figure 2.7.

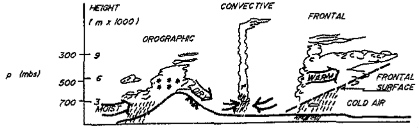


FIGURE 2.7 Precipitation Mechanisms

In the consideration of a landfill site location it may be important to note the mechanisms of rainfall. For example winds approaching mountains in a normal direction will deposit rain on the windward slope leaving the leeward slope comparatively dry. Generally the rainfall characteristics of a region depend on :

a) distance from source of moisture supply

b) prevailing wind movements

c) altitude

d) location with respect to mountain ranges

e) location with respect to paths of cyclonic storms.

The measurement of rainfall (using a standard *rain* gauge) is perhaps the easiest of all the elements in the water balance although there are always inaccuracies in the measurement. Hills or forest clearings affect the quantity of rainfall in the specific area while splash (in and out), wind and turbulent eddies will affect the interception. The British Meteorological Office specifies that the rim of the gauge should be one foot above the ground (Penman [55]).

If rainfall figures from a nearby meteorological station are used, they must be used with caution, and if possible, correlated *with a site-specific gauge.*

2.4.2 Evaporation, Transpiration and Evapotranspiration

Evaporation is *perhaps* the most difficult element of the water balance to measure or calculate. In fact Olivier (56) writes "It cannot be stressed strongly enough that no formula, complex or otherwise, can ever provide a "push *button solution*" to *the* problem of determining evaporation."

The fundamental theory of evaporation is usually accredited to Dalton (1802). He stated that evaporation rates are proportional to the difference between the vapour pressure at the water surface (e_w) and the actual vapour pressure in the air just above the surface (e_a). Or in equation form :

$$\text{Evaporation } E = C\ (\ e_w - e_a\ )$$

However there are a number of main factors which affect evaporation:

a) Temperature - the vapour pressure of a body of water increases as the temperature increases, causing evaporation. Plotting mean figures at Linbro Park from 1978 to 1988, Figure (2.8), shows that evaporation is greater on a warming cycle than a cooling cycle at the same temperature.

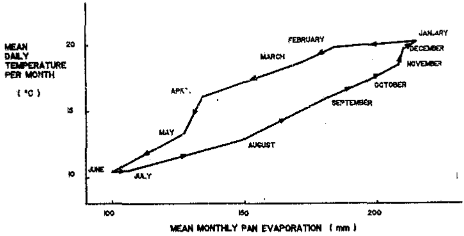


FIGURE 2.8 LINBRO PARK LANDFILL 1978 to 1988.

b) Wind - Wind is effective in removing water molecules in the air immediately above the water and bringing in air capable of holding more water vapour. Advection may also occur when a cool air mass passes and decreases evaporation or even abstracts heat from the underlying surface causing condensation.

c) Atmospheric pressure - this applies primarily on the macro scale where a higher altitude has a lower atmospheric pressure thus causing more molecules to escape the surface in the form of evaporation.

d) Soluble Solids - evaporation from salt solutions (e.g. sea water, landfill leachate) is reduced since the evaporation rate is proportional to the difference in vapour pressures of water and atmosphere. It was found by Rohwer, Lee and Adams (Chow (30)) that the evaporation rate decreases as the specific gravity of the solution (i.e. the solute concentration) increases.

e) Nature and shape, and colour of surface - Vapour pressure for a body of water with a convex surface is greater than that with a flat surface which is greater than that with a concave surface under the same conditions (Chow (57)). However, these differences are only important for radii of curvature of micron size. Evaporation from black painted pans was found to between 10 and 25% more than from white painted pans (Houk (58)), because of the difference in heat absorption of the two surfaces.

The measurement of evaporation and transpiration is not a simple task and it is recommended that from the 10 or more standard evaporation pans available (Chow (57) and Houk (58)) the most popular one i.e., the US Weather Bureau Class A land pan (4 feet in diameter, 10 inches high set on a timber grillage with base 6 inches above ground) be used. This is a standard pan used by the South African Weather Bureau and it makes comparisons of various measurements that much simpler. There are problems in measurement such as rain effects, splash (from wind, hail or rain), surging in floating pans, absorption of solar radiation, and differing materials and colours. Conversion coefficients have been developed to equate pan evaporation to lake or reservoir evaporation. Schulz (59) has equated Class A pan coefficients in eight different areas to get an average coefficient of 0,73 (i.e. Actual evaporation = 0,73 x pan evaporation). Gray [54] studied 12 different Class A pans to get an average coefficient of 0,70.

Evapotranspiration which includes the effect of transpiration by plants can be measured in a lysimeter containing sample crops and measuring input and output (by weighing) or by measurement of soil moisture changes using neutron probes, tensiometers or resistance blocks.

A number of prediction formulae have been used to calculate potential evaporation or evapotranspiration. Linsley and Franzini [60] estimate potential evapotranspiration from a vegetated soil surface to be equivalent to free water evaporation. This is supported by Rovers and Farquhar [61] who maintain that evapotranspiration can result in losses equal to evaporation from a free water surface.

Table 2.4 shows a few selected evaporation equations and Fig 2.9 shows their correlation with measured evapotranspiration.

Considering evaporation from bare soil is, or may be, very different if the soil is unsaturated. Evaporation at a soil surface sets up a suction gradient which tends to move water to the surface. As the soil dries the suction of the soil increases. For coarse grained soils the effect of evaporation on a relatively dry soil does not penetrate as deep as for fine

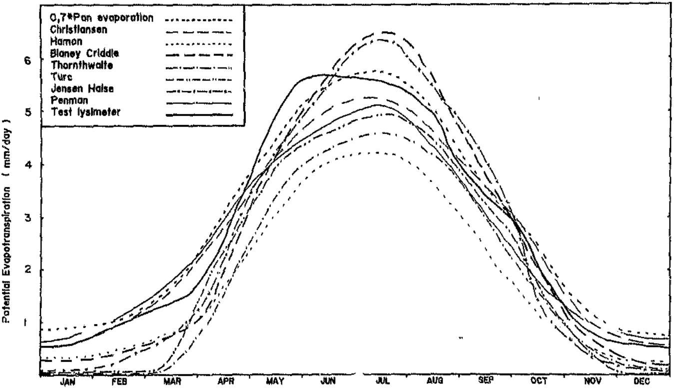


FIGURE 2.9 Comparison of measured averag' daily potential evapotranspiration with computed values using various equations. (ex Schulz (59))

soils and clays (Penman [55]). The California State Water Pollution Control Board [62] considers that evaporation from bare soil to a depth of 203 mm (8 inches) is maximum, which is backed up by Rovers and Farquher [69]. Fenn et al [47] confirm this figure (200mm) and add that evaporation from bare soil is roughly equal to half the precipitation for heavy soils and 30% of precipitation for sandy soil.

Wheater and Sherrat [63] show that a plot of moisture content versus time at a given layer in the soil can indicate the onset of evaporation Fig (2.10)

Results based on this method show reduced estimates of evaporation and increased estimates of percolation, as compared to field capacity estimates, by between 28 and 50%. The field capacity estimate assumes that percolation will cease at field capacity and any further reduction in moisture will be evaporation.

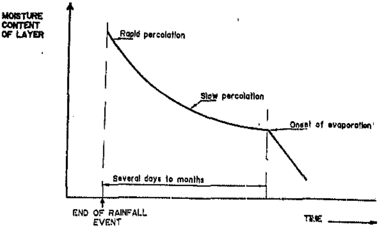


FIGURE 2.10

Table 2.4

NAME OF EQUATION	EQUATION
Lowry - Johnson	E (acre feet/acre) = $0,8 + 0,156\, I_F$
Thorthwaite	E (cm/month) = $1,62\ (10T/I)^a$
Blaney - Criddle	E (inch/month) = KF
Jenson - Haise	E (mm/day) = $(0,14T - 0,37)R_s$
Turc	E (mm/annum) = $P/(0,9 + (P/L)^2\ )^{0,5}$
Blaney - Morin	E (inch/month) = $Ktp\ (114 - h)$
Hamon	E (inch/annum) = $\rho_s CD$
Penman	E (mm/day) = $f(\Delta(R_s(1-r)(0,22 + 0,55n/N)) - (\sigma T_a{}^4\ (0,56 - 0,09e_d{}^{0,5})(0,1+0,9n/N)) + (0,175 + 0,0035u_2)(e_a - e_d))/(\Delta + \gamma)$
Christiansen	E (mm/day) = $0,473\ R_s\ C_t\ C_h\ C_w\ C_s\ C_e\ C_m$
Linsley & Franzini	E = 0,7 x class "A" pan evaporation

where: E = Potential evapotranspiration

I_F = $\Sigma t_{max}(daily)/1000$ for $t_{max} > 32$ ^oF

t = temperature (^oF)

T = mean daily temperature (^oC)

I = Σi_j

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

a = $6,75 \times 10^{-9}\ I^3 - 7,71 \times 10^{-7}\ I^2 + 0,01792\ I + 0,49239$

K = a crop constant

F = $\Sigma tp/100$

p = monthly percentage of daytime hours in the year

R_s = Solar radiation at the top of the atmosphere (mm/d)

P = Precipitation (mm/annum)

L = 300 + 25T + $0{,}05T^3$

h = mean monthly relative humidity (%)

C = 0,55 cm/g year

D = possible sunshine hours in 12 hour units

Δ= Slope of the saturated vapour pressure vs. temperature curve at t_a

γ= Psychometric constant = 0,49 mmHg/°C

r = Albedo

n/N = Ratio of bright sunshine to sunshine

σ= Stefan-Boltzman constant = $2{,}01\times10^{-9}$ mmHg/d

T_a = Absolute mean daily air temperature (K)

U_2 = Mean wind velocity at 2metres (miles/hour)

e_d = Saturated vapour pressure at dew point

e_a = Saturated vapour pressure at t_a (mm Hg)

C_t = $0{,}393 + 0{,}5592(T/20) + 0{,}1722(T/20)^2$

C_w = $0{,}708 + 0{,}3276(W/96{,}56) - 0{,}036(W/96{,}56)^2$

W = Wind speed (km/day)

C_h = $1{,}25 - 0{,}348(H/40) + 0{,}12(H/40)^2 - 0{,}0218(H/40)^4$

H = Mean relative humidity measured at noon (%)

C_s = $0{,}542 + 0{,}64(S/80) - 0{,}4992(S/80)^2 + 0{,}3174(S/80)^3$

S = n/N (%)

C_e = 0,97 + 0,03(E/1000)

E = Elevation above mean sea level (feet)

C_m = Monthly vegetative coefficient

2.4.3 Runoff

Surface runoff depends on many factors including intensity and duration of storm, antecedent soil moisture conditions, permeability and infiltration capacity of the soil, the surface slope, amount and type of vegetative cover and drainage characteristics.

The oldest of the runoff estimation equations is the Rational Formula which is recommended for very small watersheds of up to 100 acres (Schulz [59]).

$$\text{Runoff } Q \ (m^3/s) = 0,278 \ CIA$$

where: C = runoff ratio = runoff/rainfall

i = rainfall intensity (mm/h)

A = Watershed area (km^2)

For evaluation of the water balance in leachate production the actual flow is unimportant and the runoff ratio C will give an estimate of total quantity of runoff in mm. Values of C as given by Fenn et al [47] and Robinson [64] are shown in Table 2.5.

Table 2.5

SURFACE	SLOPE	C
Grass - sandy soil	flat 2%	0,05 - 0,10
	2% - 7%	0,10 - 0,15
	greater 7%	0,15 - 0,20
Grass - heavy soil	flat 2%	0,13 - 0,17
	2% - 7%	0,18 - 0,22
	greater 7%	0,25 - 0,35

Alternatively a method of estimating runoff while taking into account soil condition at different times was developed by the United States Soil Conservation Service of America (SCS) and is described by Wanielista (65) and Noble (82). The SCS analysed over 3000 soil types and divided them into four hydrologic groups depending on their drainage characteristics and runoff potential. Three antecedent soil moisture conditions are described from dry to wet and a number of curve numbers were developed for different land uses. Soil moisture and excess rainfall available for runoff can then be calculated. The process is described in detail in Appendix A.

2.4.4 Infiltration and percolation

Infiltration is that part of the hydrologic cycle that transports precipitation into the ground. Percolation will only occur if the receiving soils are saturated (Wanielista [65]).

The depth of water which can be stored is estimated by

$V = n(1 - S)D$

V = depth of soil water storage
n = porosity
S = fraction of average saturation
D = depth to groundwater.

Yong and Warkentin [66] refer to the outflow principle where a difference in textures of 2 different layers is large then soil suction will control movement. Thus water infiltrating a clay which meets a gravel layer will stop until zero suction occurs (i.e. saturation) before moving into the coarse grained layer. Goode [67] supports the theory in his paper on selecting soil covers for the so called "wick effect". No literature has been found by the author to back this up in a soil/waste boundary condition, but it is assumed to be valid when considering the municipal waste grain size distribution shown in Figure 3.10.

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Percolation is the infiltration that takes place after the soil or refuse reaches its field capacity. Field capacity is defined as the maximum moisture content which a soil or refuse can retain in a gravitational field. Fungaroli (66) states that the field capacity of refuse changes during its life cycle and also increases as the size distribution decreases.

Rovers and Farquhar (61) quote refuse moisture retention figures of 51% (England 1961), 57% (England 1961) and 54% (Virginia USA 1970). Their own figure of 314kg/m^3 equals 70% (Canada 1973). Young and Barber (69) quote a figure of 15% to 32% for domestic waste (1979). This represents retention of additional water, so if the initial moisture is added, the figures are more like 35% to 52%. Holmes (64) gives figures of between 63% and 74%, related to refuse densities between 638kg/m^3 and 960 kg/m^3 for aged refuse, (more than 4 years old), (England 1980). Campbell (65) quotes a figure of 82% (England 1983) for fresh refuse. Fenn et al (47) indicate that the field capacity is between 50% and 88%.

All the figures are based on a moisture content calculated as a percentage of the mass of dry refuse. Where it has been necessary to convert from figures of inches/foot or mm/m, an appropriate refuse density has been assumed.

2.5 Attenuation and containment design philosophies

There is world wide debate on which design philosophy is the most appropriate. Western Europe appears to favour the containment concept while Britain seems to favour the Attenuation approach. Ball and Blight (29) express the view that in South Africa the merits of each philosophy should be considered in relation to each different site and situation.

The containment design relies on an impermeable liner and an effective leachate collection network. The draft guidelines (66) classify a containment site as a class one site for the disposal of hazardous and toxic wastes. An acceptable liner would be a synthetic liner or an in situ or imported clay with coefficient of permeability of less than 1 x 10^{-6} cm/s.

Attenuation design relies on the soil below the landfill to cleanse the leachate. The different attentuation mechanisms described by Bagchi (70), Robinson (71), Fuller (72) and others are listed below :

1. Adsorption - the adhesion of molecules onto the surface of individual clay particles. Note that adsorption, which reduces total dissolved solids (TDS), is not an exchange reaction where

TDS would remain unchanged.

2. Biological uptake - micro organisms may break down, retain or adsorb leachate constituents.

3. Cation exchange - can come from isomorphous substitution, broken bonds and edges or replacement of an H^+ ion with another ion (usually Na^+ , Ca^{++} ,etc.). The ease of replacement depends on size, valence and mass action and for clay minerals, cation exchange capacity (CEC) increases from kaolinite to illite to chlorite to smectite.

4. Anion exchange - little is known about it [illegible] . increases as the pH decreases.

5. Dilution - chloride, nitrate, sodium, hardness and sulphate are not attenuated by soil but the concentration is reduced by dilution in the groundwater.

6. Filtration - where constituents are physically entrapped in the random pore structure of the soil.

7. Chemical precipitation - occurs from a phase change where crystals in excess of the solubility limit are deposited. It depends on the ions and their concentration, temperature, pH, redox potential (EH) and the concentration of the dissolved substances and their solvent.

To obtain adequate attenuation of the leachate the soil must be able to utilise most of the above mechanisms. Thus a soil is required with a low enough permeability to allow the reactions to take place, but not too low as to cause ponding. A high cation exchange capacity, buffering capacity (i.e. resistance to changes in pH), organic content, clay content and a well graded particle size distribution are all desirable. The ground water must be fairly deep and flowing faster than the infiltrating leachate.

The problem in the design of attentuation sites is summed up by Roulier (42) who states that "....it would be nearly impossible to extrapolate measurements in one soil leachate system to predict behaviour in another".

3. RESEARCH STRATEGY AND METHODOLOGY

3.1 Background to Linbro Park sanitary landfill

Linbro Park is situated in the Sandton municipal area to the North East of Johannesburg. It is a regional site serving Johannesburg, Sandton and Alexandra municipalities. The site started in a borrow pit for the construction of the N3 motorway in 1969. It has two phases of construction, the North phase which occupies about 3,5 million m^3 of airspace is almost complete and the South phase is due to commence early in 1989.

Refuse input at Linbro is presently at a rate of 220 000 tonnes per annum. Input consists primarily of urban wastes with a composition as shown in Table 3.1. Toxic, hazardous and liquid wastes are not accepted at the site.

TABLE 3.1 Waste Input at Linbro Park

Gardens, streets and stands	6,9%
Domestic waste	15,0%
Bulk containers (includes large office and shopping complexes, factories and businesses)	62,6%
Builders rubble and soil	15,0%
Industrial (non hazardous waste)	0,5%

National awareness of the leachate and gas problems associated with sanitary landfills in South Africa only became prominent in the late 1970's and as such the North phase of the site began without a preliminary hydrogeological investigation. The Johannesburg City Council however operated the site according to strict sanitary landfill standards and kept well above the ground water table, thus minimising the risk of pollution.

The operation involves placing refuse between two parallel sand or rubble berms spaced about 30m apart, and compacting the refuse within this cell in thin layers to a height of about 2m. The refuse is then covered with a 150 to 300mm layer of soil at the end of each working day. See figure 3.1.

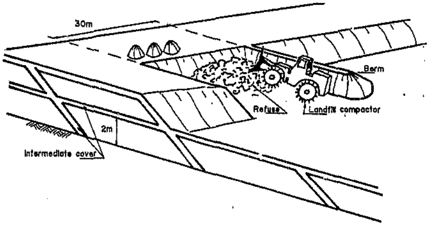


FIGURE 3.1 Cell construction at Linbro Park

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 (CC)
		1983	1983	1986	1985	1986	1987	1988	1987	1988	1988	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	6,0	5,5 to 9,5
C.O.D		10	10	200	220	180	10	26	15	30	20	26575	1605	75
T.D.S		140	51	210	62	69	170	230	180	150	160	10800		
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	55	31	30	7175		250
ALKALINITY		40	22	140	54	47	77	28	80	59	96	4317		
HARDNESS	650	65	2	200	33	96	140	89	77	90	97	2590		
CHLORIDE	600	11	4	0	2	0	23	13	20	9	6	2000		
POTASSIUM		4	5	1,9	2	2	2,5	6	2,3	5	3	860		
SODIUM	400	16	18	16	10	18	24	13	23	16	24	1638		10+intake

TABLE 3.2 Ground water monitoring *results at Linbro Park* as compared to 'standards'.

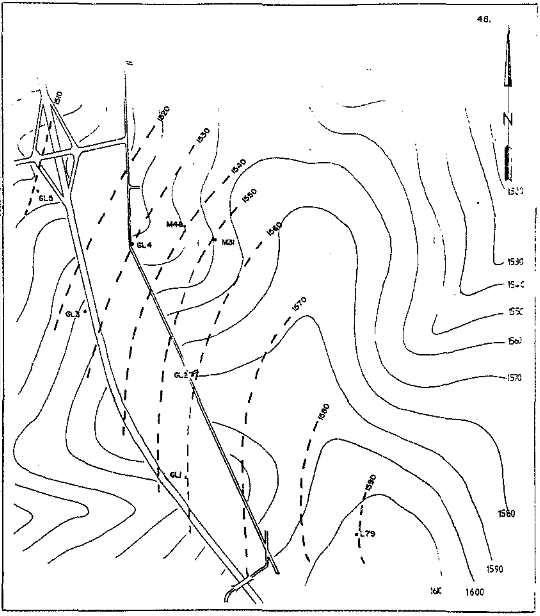
All units in mg/l except pH and conductivity (mS/m)

Figure 3.2 shows the groundwater contours in the Linbro Park area calculated from boreholes drilled on the site and within some residential properties in the suburb. The cross sections as shown in figure 3.3 indicate the depth to which filling has taken place on the site. The site originally traversed a natural drainage channel. For this reason a culvert was constructed along the length of this channel and the fill was placed over the culvert. Surface water flow directions to the site and through the culvert are shown in Figures 3.4 (a) and (b).

In 1978 surface water sampling and analysis was undertaken at Linbro Park and then extended to ground water sampling in 1983. Favourable results were found as shown in Table 3.2. Positions of monitoring holes and surface monitoring points are shown in Figure 3.2.

Geologically Linbro Park is located on the Johannesburg - Pretoria granite dome, consisting primarily of weathered granites in different stages of decomposition. See Figure 3.5

Two other sites have been used to a very limited extent for comparative purposes. The first is the Waterval landfill in the Johannesburg western areas. This is of interest as it is a site in a water deficit area but started with wet tipping in 1928 and is thus in hydraulic continuity with the groundwater. The second site is the Coastal Park Site operated by the Cape Town City Council which represents a site in a water surplus area.



Positions of monitoring holes and other boreholes with the corresponding determination of ground water contours.

LINBRO PARK

SCALE 1: 15 000

FIGURE : 3.2

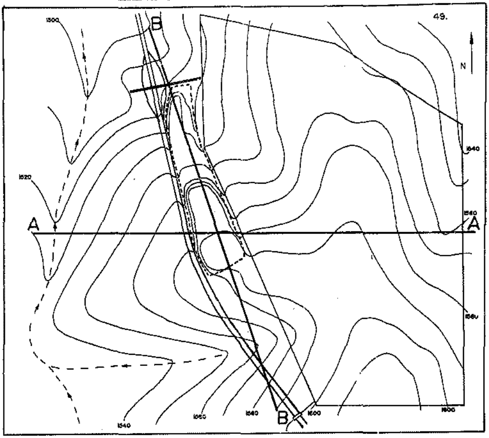
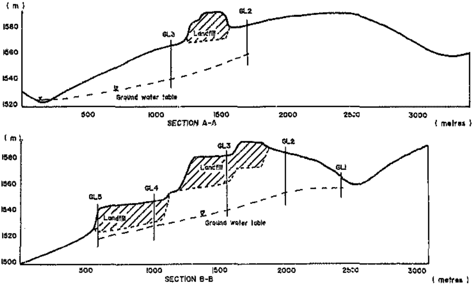
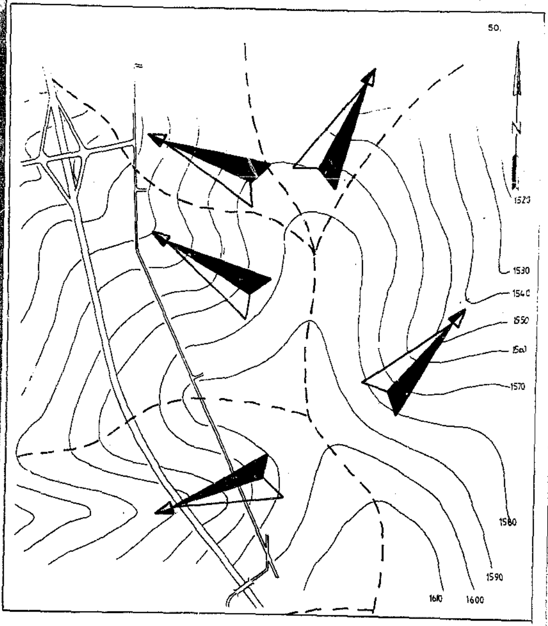


FIGURE 3.3 PLAN OF THE LINBRO PARK AREA SCALE 1 : 20 000



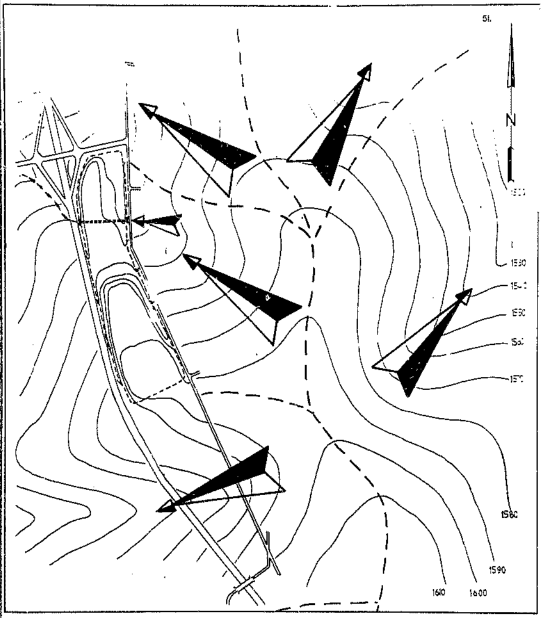


Contours before landfilling operations commenced, showing watersheds and surface water flow in the area.

LINBRO PARK

SCALE 1: 15 000

FIGURE : 3.4 (a)

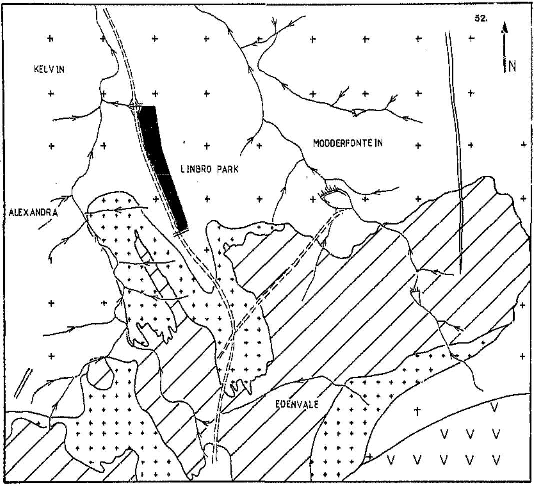


Contours after completion of the northern phase, showing watersheds and surface water flow in the area.

LINBRO PARK

SCALE 1: 15 000

FIGURE : 3.4 (b)



ex. C.R.ANHAEUSSER "Geological plan of the Johannesburg-Pretoria granite dome" Scale: 1 : 50 000

HOMOGENOUS MEDIUM GRAINED GREY GRANODIORITE SUITE (in places slightly porphyritic also displays occasional weak banding and small isolated mafic xenoliths) Pegmatites are common

HORNBLENDE AND/OR BIOTITE GNEISSES (hybrid mafic, ultramafic, and granite rocks and dioritic gneisses.

SWAZILAND SEQUENCE ; Undiferentiated mafic and ultramafic plutonic, and volcanic rocks now mainly altered to serpentinites a variety of amphibolites (hornblende, tremolite, actinolite) and chlorite talc shist.

VENTERSDORP SEQUENCE : Undiferentiated intermediate -to-acidic volcanic rocks, agglomerates and pyroclastics, some sediments.

MAFIC DYKES (diabase and dolerite)

ROADS

RIVERS (with flow direction)

FIGURE 3,5

3.2 Plan of the study

The generation of leachate depends on a number of factors, including the hydrologic cycle, the nature and properties of the refuse, of the soil cap and of the soil in the unsaturated zone. This research aims at correlating the various parameters, measured and calculated, so that a prediction of the generation and movement of leachate through the fill and into the unsaturated zone can be made. This prediction will then be correlated with actual site observations. The procedure can be seen in the flow diagram shown in Figure 3.6.

Rainfall and evaporation figures have been measured on site and from these a water balance model can be developed to predict infiltration through the soil cap.

Soil cap parameters such as permeability, field capacity, depth and vegetation have been measured to evaluate how much of the infiltrating water will actually reach the waste layer and percolate downwards.

The refuse itself has certain parameters such as permeability and field capacity, which influence the migration of water through it. These parameters have been measured in the laboratory. Confirmation of the predictions of water movement through the refuse have been produced by sampling of large diameter auger

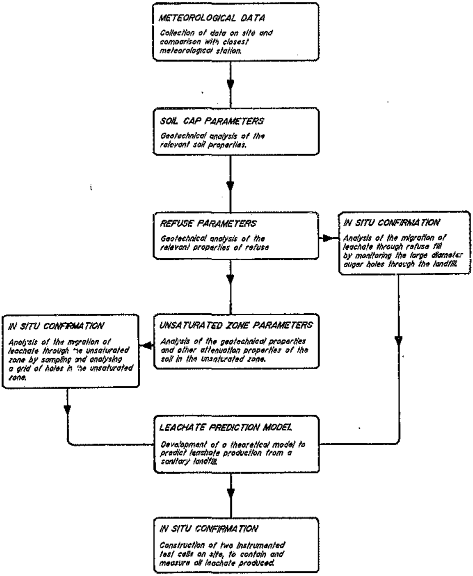


FIGURE 3.6 RESEARCH PLAN

holes through the refuse.

Leachate reaching the base of the fill will be able to percolate into the underlying unsaturated zone. Soil parameters for attentuation in the unsaturated zone have been measured in the laboratory. Field correlation has been done by excavating a grid of five holes from the toe of the fill moving away perpendicular to the toe, and sampling soil the holes at different depths.

The available data has been used to develop a prediction model for leachate migration. The final test of this model is two test cells or lysimeters constructed on site and instrumented to catch any leachate produced.

3.3 Meteorological data :

A mini-meteorological station was set up at Linbro Park in early 1987. Instruments are a maximum/minimum thermometer, rain gauge, class A evaporation pan, anemometer, hygrometer and a barometer.

The maximum/minimum thermometer is read once a day and the mean of the two temperatures gives mean daily temperatures in degrees Celsius.

The rain gauge is a simple conical gauge with a maximum capacity of 100mm and is read once a day when precipitation occurs.

The evaporation pan is a United States Weather Bureau class "A" land pan and evaporation is measured, using a hook gauge evaporimeter in a stilling well, once a day. Due to shipping delays in importing the evaporimeter, measurements of evaporation have only been taken from July 1987 onwards.

A hand held anemometer has been used for 3 daily wind speed measurements above the evaporation pan. Unfortunately 3 spot measurements were not really adequate because of the gusty variation in wind throughout the day and with hindsight a continual readout of wind speed would have been preferable.

The hygrometer measuring relative humidity was read three times a day at 08h00, 12h00 and 16h00. As with the anemometer a continual readout would have been preferable but the readings were adequate to apply to some of the potential evapotranspiration formulae.

The barometer measuring atmospheric pressure (in mbar) was read three times a day with all readings appearing in the range 1034 to 1037 mbar.

Similar meteorological data was obtained from the South African Weather Bureau in Pretoria for the meteorological station at Jan Smuts airport (14 Km East of Linbro Park). Evaporation data was only available from 1978 onwards but all other data was obtained

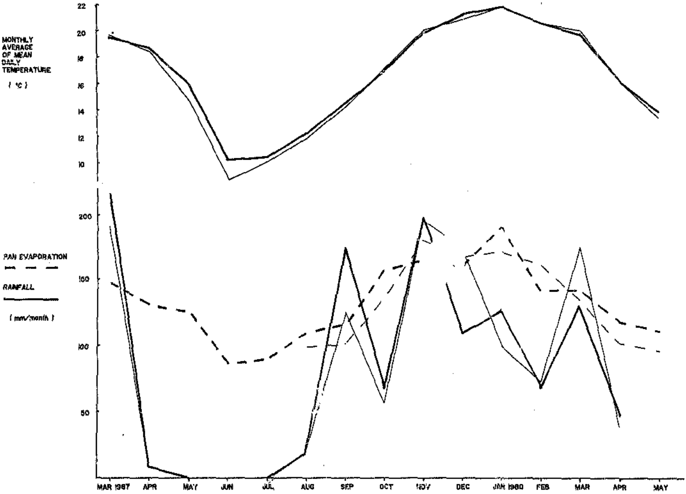


FIGURE 3.7 COMPARISON OF METEOROLOGICAL DATA AT LINBRO PARK AND JAN SMUTS

JAN SMUTS ———— LINBRO PARK ————

on a daily basis from 1969 (the start of the site). A comparison of rainfall, pan evaporation and mean daily temperatures for one year between *Linbro Park* and *Jan Smuts* is shown in Figure 3.7, and table 3.3.

Table 3.3.

	Jan Smuts	Linbro Park	Difference (%)
Annual Rainfall (mm)	948	944	0,4
Annual pan evaporation (mm)	1558	1507	3,3
Mean daily temperature over the year (°C)	16,5	16,2	1,8

It was thus considered safe to use the statistics given at the Jan Smuts station for long term predictions of water balance at Linbro Park. The means and standard deviations of monthly rainfall, evaporation and mean daily temperatures are shown in Figure 3.8.

The trend indicates six relatively wet' months, October to March, and six relatively dry months, May to September.

Using the above averages and other relevant figures and applying

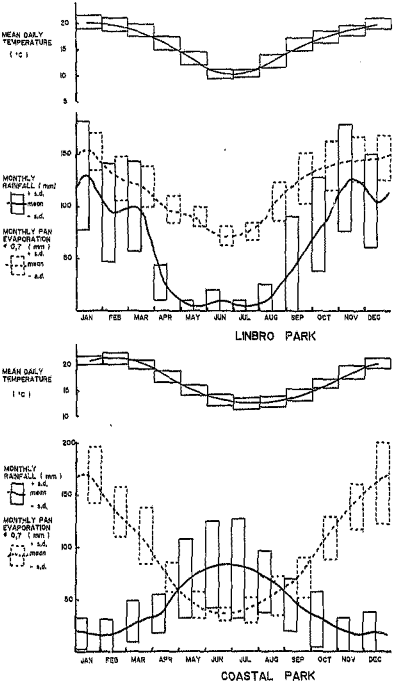

MEAN DAILY TEMPERATURE (°C)
20
15
10
5
MONTHLY RAINFALL (mm)
+ s.d.
mean
- s.d.
MONTHLY PAN EVAPORATION × 0,7 (mm)
+ s.d.
mean
- s.d.
150
100
50
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
LINBRO PARK
MEAN DAILY TEMPERATURE (°C)
20
15
10
MONTHLY RAINFALL (mm)
+ s.d.
mean
- s.d.
MONTHLY PAN EVAPORATION × 0,7 (mm)
+ s.d.
mean
- s.d.
200
150
100
50
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
COASTAL PARK

FIGURE 3.8

the various prediction formulae for potential evapotranspiration from Table 2.4, Table 3.4 shows the wide range in predictions from the different *formulae:*

FORMULA	POTENTIAL ET.
Thornthwaite	807 mm/annum
Christiansen	1541 mm/annum
Blaney Criddle	937 mm/annum
Lowry Johnson	1509 mm/annum
Penman	724 mm/annum
Turc	596 mm/annum
Linsley and Franzini (pan evaporation x 0,7)	*1387* mm/annum

Table 3.4.

With an average rainfall of 747mm Turc and Penman predict a water surplus, while the other formulae predict a water deficit.

The above analysis is done on an annual basis, however there could be seasonal periods of water surplus during the year, potentially causing leachate production, even though there is a water deficit on an *annual basis. In this case* a daily water balance would be a more accurate prediction tool than a weekly or even monthly water balance calculation.

Daily, weekly and monthly water balances *have been* calculated at *Linbro Park for* 1 *year* using the method of Thorthwaite and Mather (73) as adapted by Fenn et al (47). The method is described in Appendix C, from the start of wet season in 1987 to the start of the wet season in 1988. Mean figures taken over *20 years* at *the* Jan Smuts *Meteorological* station are also included. Results of varying the different parameters are shown in table 3.5 below.

TABLE 3.5

Depth of soil subject to e/tpn.	Evapor'n data	Rainfall data	Runoff formula	Calcul'n period	Annual percolat'n
1.USING FIGURES FOR ONE YEAR 1987 TO 1988					
1000mm	0,7xPan	Measured	S.C.S	Daily	68 mm
1000mm	0,7xPan	Measured	0,1125xP	Daily	133 mm
1000mm	0,7xPan	Measured	S.C.S	Weekly	Nil
1000mm	0,7xPan	Measured	0,1125xP	Weekly	92 mm
1000mm	0,7xPan	Measured	S.C.S	Monthly	Nil
1000mm	0,7xPan	Measured	0,1125xP	Monthly	4 mm
200mm	0,7xPan	Measured	S.C.S	Daily	181 mm
200mm	0,7xPan	Measured	0,1125xP	Daily	264 mm
200mm	0,7xPan	Measured	S.C.S	Weekly	44 mm
200mm	0,7xPan	Measured	0,1125	Weekly	179 mm
200mm	0,7xPan	Measured	S.C.S	Monthly	29 mm
200mm	0,7xPan	Measured	0,1125	Monthly	101 mm

table 3.5 (cont.)

Soil depth	Evapor'n data	Rainfall data	Runoff formula	Period	Percolat'n
2. USING 20 YEAR MEAN FIGURES (1968 TO 1988)					
1000mm	0,7xmean	mean	0,1125xP	Monthly	Nil
1000mm	Thornth- waite	mean	0,1125xP	Monthly	Nil
1000mm	0,7xmean	mean + sd	0,1125xP	Monthly	Nil
1000mm	0,7(mean - sd)	mean + sd	0,1125xP	Monthly	35 mm
1000mm	Thornth- waite	mean + sd	0,1125xP	Monthly	272 mm
200mm	0,7xmean	mean	0,1125xP	Monthly	Nil
200mm	Thornth- waite	mean	0,1125xP	Monthly	28 mm
200mm	0,7xmean	mean + sd	0,1125xP	Monthly	25 mm
200mm	0,7(mean - sd)	mean + sd	0,1125xP	Monthly	104 mm
200mm	Thornth- waite	mean + sd	0,1125xP	Monthly	301 mm

3.3.1 Remarks

A number of simplifications and assumptions had to be made in producing the figures in Table 3.5 as indicated :

1. *Fenn* et al state that evaporation from bare soil does not extend below 200mm. In this case the intermediate soil cover and final soil cover before vegetation have been considered as layers with 25mm water holding capacity (*field capacity to wilting point*).

2. After vegetation of the final cover with shallow rooted crops (i.e. grass) on soil, between a sand loam and a *silt loam, soil* moisture *retention would* be 100mm (Table 10 from Thornthwaite (79)) for a 1m layer of final cover.

3. Two sets of data are used : a) Daily measurements between 1 September 1987 and *31 August 1988 and* b) Monthly means and standard deviations from figures measured between 1968 and 1988 by the S.A. Weather Bureau for the Jan Smuts meteorological station.

4. *Potential* evapotranspiration was calculated using pan evaporation multiplied by a factor 0,7, or alternatively using figures based on mean daily temperatures, hours of sunshine and angle of latitude as expressed by Thornthwaite (79).

5. *Runoff* was calculated using the American Soil Conservation Service method explained by Wanielista (41), which was only accurate *for daily calculations because* it used antecedant soil moisture conditions, or alternatively by using the runoff coefficient. The coefficient *can be found from Table 2.5* and is considered to be between a sandy and a heavy soil on a relatively flat slope 2%. Thus a factor of 0,1125 was used.

6. Different extreme situations were investigated using the 20 year mean figures :

i) Precipitation was increased by adding the standard deviation
ii) Evaporation was decreased by subtracting the standard deviation while using the increased precipitation figures.

The results of Table 3.5 show that percolation figures are difficult to predict with any confidence. For the 200m cover, percolation *varied between nil and 301mm per annum*, with a mean and standard deviation of 114mm $\pm$ 99mm per annum. Percolation below the vegetated 1m cover was *calculated as between nil and* 272mm per annum with a mean and standard deviation of 55mm $\pm$ 81mm per annum. For the extreme conditions, the upper limits were assumed to be the annual percolation.

i.e. percolation below 1m vegetated cover = 136mm/annum and
percolation below 200mm bare soil cover = 213mm/annum

It should be stressed at this point that there are a number of other factors which affect this percolation figure :

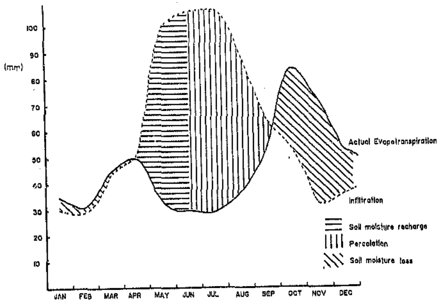
a) Ponding - there could well be ponding of surface water in areas where landfill settlement has occurred or where final grades are too flat to encourage runoff. This could be a problem when the end use of a landfill is a sportsfield which requires a level surface.

b) Surface cracking - often caused by differential settlement of the landfill or the drying out of a high plasticity clay liner, cracks form in the surface of the landfill and allow a direct passage for water to flow into the waste.

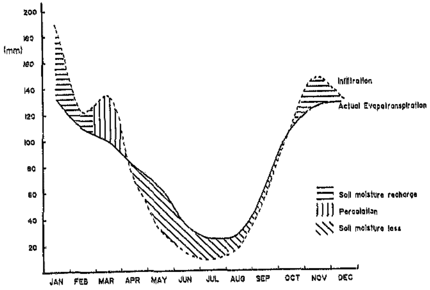
c) Surface erosion - is often the result of steep slopes, lack of vegetation or the use of dispersive soils as a cover. This leads to a reduction in the thickness of the cover and often results in direct channels into the waste.

d) Open waste during operation - if rain occurs during daily operations the rain will quickly be soaked up by the waste and very little runoff will occur. An intermediate layer of soil will be placed on top of the waste at the end of the day, thus restricting evaporation. The rainfall on that day will then all contribute to percolation.

e) Direct channels of coarse material through the fill to the base are a source of percolation which may cause leachate to be produced even before the landfill has reached its field capacity.



COASTAL PARK WATER BALANCE



LINBRO PARK WATER BALANCE

FIGURE 3.9 Infiltration curves for Linbro Park and Coastal Park

A Water Balance was also calculated for Coastal Park and is compared to that of Linbro Park in appendix H. The curves showing Actual evapotranspiration and infiltration are shown in figures 3.9. The figures for Coastal Park were obtained from the meteorological station at D F Malan Airport (16km NE of the site). Assumptions for both sites are the same (i.e. 1m top cover with 100mm available soil storage, potential evapotranspiration equals 0,7 x (mean Pan evaporation - standard deviation) and rainfall equals mean plus standard deviation). Runoff for Linbro Park = 0,1125P while that at Coastal Park = 0,075P, due to the sandy nature of its cover soil.

Coastal Park receives less annual precipitation than Linbro Park but shows a water surplus in figure 3.9. This is due to its winter rains and the reduced effect of summer evaporation due to the dessication of the soil.

3.4 Properties of soil cover

The final soil cover or cap could be a crucial factor in leachate production from a landfill. The permeability of the soil cap will influence the rate of infiltration of any rainfall, its field capacity will determine the quantity of infiltration that can be retained before it percolates into the waste, its grading, erosivity, shrinkage , swelling capacities and void ratio are also important.

Soil samples taken at Linbro Park show a particle size distribution as in Figure 3.10, determined by sieve analysis for the coarser grains and hydrometer analysis for the finer grains. It shows a well graded sandy loam with about 4% clay fraction.

Field capacity was measured by placing the soil at its in situ density, (1730 kg/m^3), into a cylinder with filter paper and drainage holes in its base. It was then soaked in water and allowed to drain for 24 hours without evaporation, and the water content measured. The field capacity varied between 13,7% and 15,9% (on a dry weight basis) with an average of 15%. From tables in Chow [57], the wilting point was predicted to be about 3%.

Permeability was measured using a constant head permeameter at various pressures and averaged $1x10^{-5}$cm/s. The specific gravity is 2,695 , void ratio 0,66 and porosity 0,4.

The attenuation properties of soil from the base of the landfill were analysed by a commercial laboratory which analysed the main cations, cation exchange capacity, pH, percentage of organic material and the buffering capacity. The results are shown in Table 3.6 and Figure 3.11.

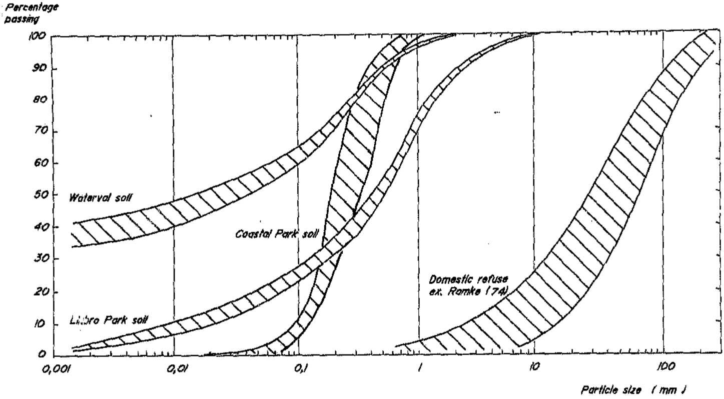


FIGURE 3.10 GRAIN SIZE DISTRIBUTION

FIGURE 3.11 SOIL BUFFERING CAPACITIES

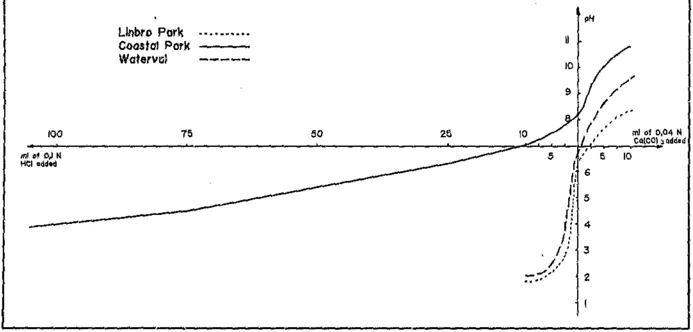


TABLE 3.6

	WATERVAL	COASTAL PARK	LNBRO PARK
POTASSIUM (mg/kg)	35	8	65
CALCIUM (mg/kg)	1203	3230	16
MAGNESIUM (mg/kg)	569	56	51
SODIUM (mg/kg)	806	29	35
pH	6,6	8,3	6,4
ORGANIC MATERIAL (%)	0,15	0,13	0,16
C.E.C (me %)	10,70	0,47	3,05

3.5 Refuse properties

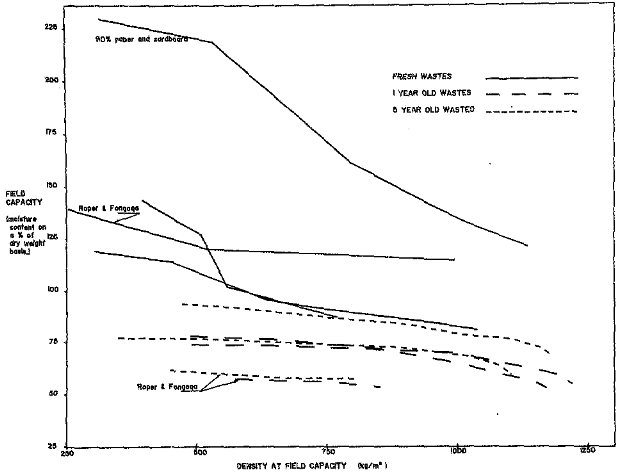
Essentially the waste can be seen as part of the soil profile but with widely differing properties. A grain size distribution of refuse was not conducted but is probably similar to that measured by Ramke (74). His grading curve is shown in Figure 3.10.

The field capacity of refuse was measured at different densities and for different ages - using the method explained in Appendix D. The general trend is for the field capacity to reduce as the density increases. The field capacity also appears to reduce with the first ageing of the refuse (initial decomposition) and then stabilizes as shown in Figure 3.12. The curves are compared with those of Roper and Fongoqa [75] who used a similar method of analysis. Table 3.7 shows other figures obtained from literature. A figure of 60% for refuse in place for over 6 months would probably be suitable for most calculations.

Table 3.7

SOURCE	FIELD CAPACITY
Rovers and	57 % (England 1961)
Farquhar [61]	54 % (Virginia 1970)
	70 % (Canada 1973)
Fenn et al [47]	50 % to 88 % (1975)
Noble [82]	109 % (Illinois 1976)
Young & Barber [69]	53 % (1979)
Holmes [84]	63 % to 74 % (England 1980)
Campbell [85]	82 % (England 1983)
Hartz & Ham [76]	67 % (1983)

Refuse permeability is also difficult to measure and depends on the type of refuse, density, age and permeant. A test has been conducted, (details in Appendix E), to determine a rough permeability figure and compare it with those found in the literature. The present test produced values between 4×10^{-3} and 2×10^{-3} cm/s. The results of these tests are shown in Figure 3.13. Figures found in the literature are shown in table 3.8.



90% paper and cardboard
FRESH WASTES
1 YEAR OLD WASTES
5 YEAR OLD WASTES
Roper & Fongaga
Roper & Fongaga
FIELD CAPACITY (moisture content on a % of dry weight basis.)
DENSITY AT FIELD CAPACITY (kg/m³)

FIGURE 3.12

TABLE 3.8 Permeability of refuse

Robinson(64)- baled municipal waste	$1{,}5 \times 10^{-2}$ cm/s at 573kg/m^3 to $7{,}1 \times 10^{-4}$ cm/s at 1137kg/m^3
Zimmerman et al(77)- milled refuse	10^{-2} cm/s at 160kg/m^3 to 5×10^{-5} cm/s at 720kg/m^3
Oweis and Kera(78)	$4{,}8 \times 10^{-3}$ to $6{,}3 \times 10^{-4}$cm/s
Hojem	4×10^{-3} to 2×10^{-3}cm/s

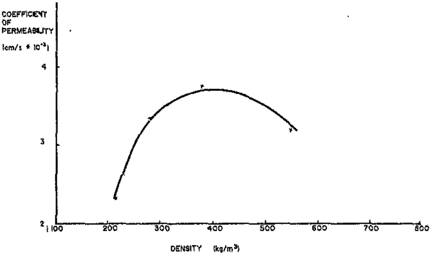


FIGURE 3.13 Household refuse permeability test

The field density of the refuse layer was, calculated at placement in the two test cells by surveying the area before and after placement and compaction of the refuse. The mass was taken off the printout at the site weighbridge. The in situ density of refuse came to an average of 989kg/m^3 . The density of the fill including soil cover was calculated during drilling of the auger hole, where all the waste was collected and weighed before disposing of it. This density was 1375 Kg/m^3.

The specific gravity of refuse was measured in the laboratory by using the vacuum method and was found to be between 1,76 and 2,38 with an average of 2,15. So an estimated void ratio of refuse (25% moisture at 989Kg/m^3)[1] is between 3,9 and 7,2 with an average of 6 and corresponding porosities between 0,8 and 0,88. The stress strain curve for refuse and the e – log p curve to give an estimate of the coefficient of consolidation have been calculated from the field capacity tests and are shown in figure 3.14.

Other engineering properties for municipal solid wastes are shown in Table 3.9.

Table 3.9

Void ratio Cancelli (79)	: 1 (well compacted), to 15 loose
Angle of internal friction (79)	: 25°
Robinson (64)	: 19°
Cohesion (79)	: 30KPa
(64)	: 63KPa
Bearing Capacity (79)	: 25 to 100 kPa (use 40 or less)

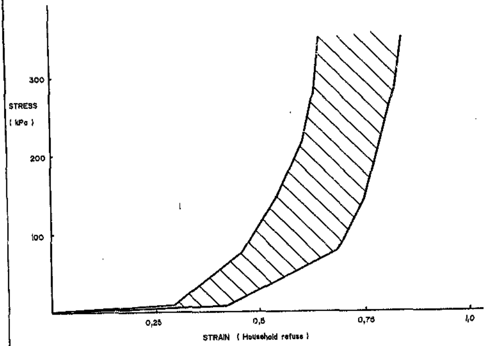
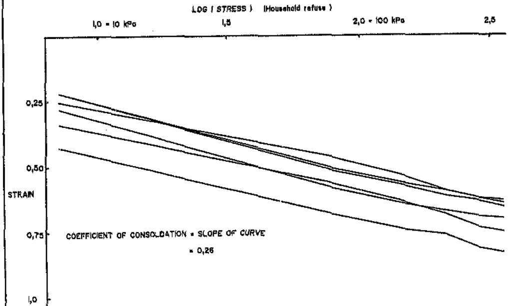


FIGURE 3.14 Refuse properties



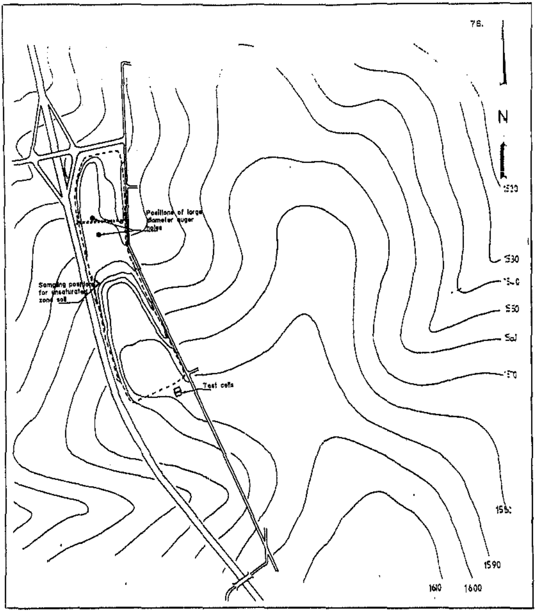
3.6 Sampling and Analysis of Refuse

Two 1,2m diameter auger holes were drilled through the refuse at Linbro Park. The positions of the holes are shown in *diagram* 3.15. A steel cage was inserted into each hole, and a collar with a lockable steel lid was placed on top. Waste samples were required at [illegible] metre down the depths of the auger holes. The holes were filled with landfill gas which made the task of sampling difficult and dangerous. Mr J.M. Ball a qualified diver with experience of sampling similar holes at Waterval and Cape Town obtained the samples, using breathing aparatus and being lowered down by means of a bosuns chair.

A similar hole has been installed at the Coastal Park site in Cape Town and sampled *in a similar fashion. An auger hole* is in existance at the Waterval landfill and has been sampled a number of times by Ball[4].

Each sample was analysed for moisture content, pH, TDS, COD, Conductivity, Alkalinity, NH_4, Cl, K and Na (See Table 3.10 for explanation of these parameters). Moisture contents were determined on a dry weight basis as shown in Appendix F.

To analyse the remaining parameters, solutes had to be extracted from the refuse. The only similar extraction process described in the *literature* was that of Houle et al (80) who used 20g of

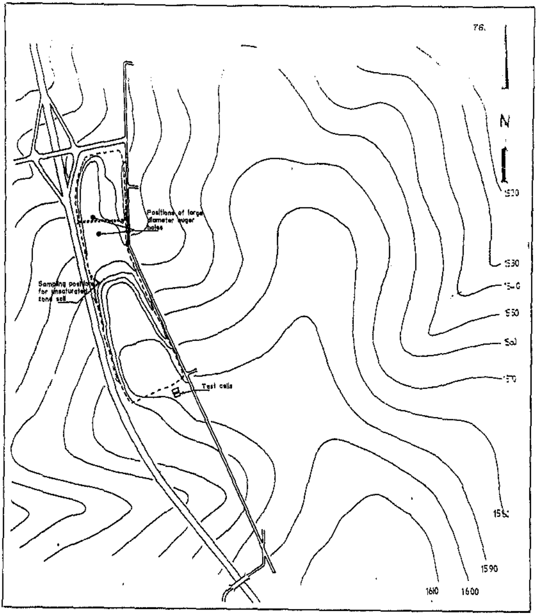


Po-itions of auger holes , test cells and grid of holes in the unsaturated zone

LINBRO PARK

SCALE 1:15 000

FIGURE 3.15



Positions of auger holes, test cells *and grid of holes* in the unsaturated zone

LINBRO PARK

SCALE 1:15 000

FIGURE 3.15

waste with 200ml of water in a Erlenmeyer flask. It was felt that 20g at each depth would not be a representative sample and a different extraction process was developed using 2 Kg samples (as explained in Appendix G).

Table 3.10. PARAMETERS USED IN ANALYSIS.

pH	pH is used to express the intensity of the acid or alkaline condition of a solution. pH is a measure of the hydrogen ion concentration in a solution.
TDS	Total dissolved solids in a liquid consists of inorganic salts, other organic matter and dissolved gases. As a general rule hardness of the water increases with dissolved solids. Total solids content of potable water ranges should not exceed 1000mg/l.
COD	Chemical oxygen demand is the total quantity of oxygen required for oxidation of a substance to carbon dioxide and water. It is essentially the oxygen required for the stabilisation of a biologically active material. Thus a high COD indicates a large quantity of potential micro biological pollution. The limitation of COD measurement is that it cannot differentiate between

biologically oxidisable and biologically inert material.

CONDUCTIVITY is a measure of a solution's ability to carry an electrical current which depends on the number and type of ions in solution and hence is related to the TDS.

ALKALINITY is the capacity of a liquid to neutralise acids. It is based usually on the carbonate, bicarbonate and hydroxide concentration. Salts of weak acids, such as borates, silicates and phosphates, some organic acids (e.g. humic acid) and salts of acetic, propionic and hydro-sulphuric acids contribute to total alkalinity. Ammonia may also contribute to alkalinity. It is thus not purely a pH dependent parameter. It is a measure of the buffering capacity of a solution to acid.

AMMONIA Ammonia is a measure of the nitrogen content and is released due to bacterial actions on urea and proteins. The ammonia concentration in aerobic conditions will decrease with time thus providing an indication of how recently pollution started. Most organic compounds containing nitrogen are derivatives of ammonia and oxidation will free the nitrogen as ammonia.

CHLORIDE	Chloride occurs in natural waters increasing in concentration as the mineral content increases. Human excreta and many industrial wastes contain chlorides which accounts for their use as a tracer.
SODIUM AND POTASSIUM	Sodium and Potassium are cations which give an indication of the salt content of a liquid.

(Sawyer and McCarty (81)).

The analysis was done by a commercial laboratory and results, including the profile of the holes, are shown in Figure 3.16. a,b and c.

3.6.1 Linbro Park North Auger Hole

3.6.1.1 End of wet season - At the end of the wet season leachate was beginning to show through the base of the soil layer at the 4,8 m level. The soil layer is well above its field capacity and contaminants (conductivity, TDS, COD, alkalinity and ammonia) are most concentrated at this level. There appears to be a build up of concentrations at the 12 m level as well with high conductivity, TDS, alkalinity, sodium and potassium. Note

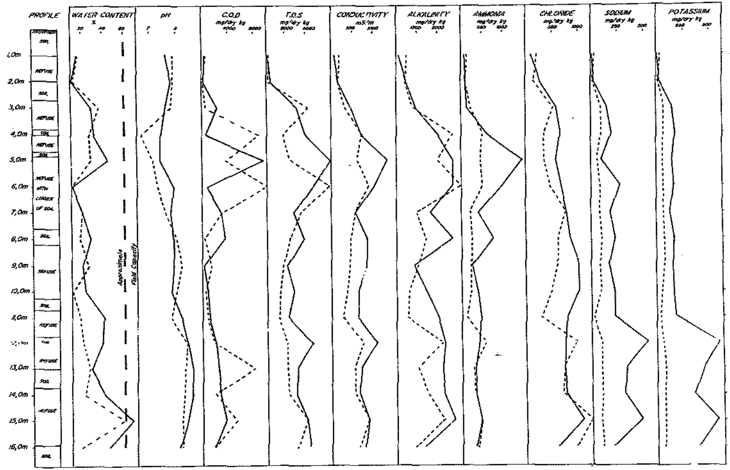


FIGURE 3.16(a) LINBRO PARK NORTH AUGER HOLE

——— end of wet season (Jun 1988)

- - - - end of dry season (Mar 1988)

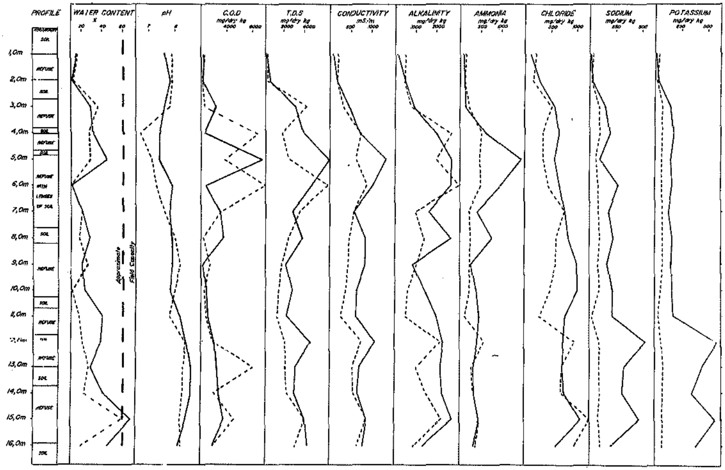


FIGURE 3.16(a) LINBRO PARK NORTH AUGER HOLE

——— end of wet season (Jun 1988)

------- end of dry season (Nov 1988)

that the pH at the 5 m level (7,4) is the lowest pH in the profile and the pH at the 12 m level (8,4) is approaching the highest pH, which is 8,6 at 13 m, and that the contamination at the 5 m level is mainly organic whereas that at the 12 m level consists of high salts.

The landfill was completed in two phases, the bottom eight metres between 1970 and 1975 and the top eight metres in 1985 and 1986. The two peaks at 5 m and 12 m would then correspond to two different sets of meteorological conditions. The two different types of contamination could be attributable to the age, state of decomposition and refuse type.

Finally there appears to be a build up of moisture and leachate concentration at the 15 m level, i.e. the base of the fill, where the refuse is at its field capacity.

3.6.1.2 End of dry season - The profile at the end of the dry season remains similar to that at the end of the wet season although there is a total reduction of moisture in the profile of 18,4%. It is interesting to note that all concentrations in the top layer have increased slightly, indicating that evaporation effects are causing an upward movement of solutes in the top layer.

The 5 m level shows a lower concentration of contaminants than the layers just above and below it. The 4 m level which has the lowest pH (6,7) has peak concentrations for conductivity, COD, alkalinity and ammonia (i.e. organic contamination) and the 6 m level has similar peaks as well as a peak in TDS concentration.

The 12 m level emulates that at the end of the wet season, showing the highest pH in the profile (8,4) and peak concentrations in conductivity, alkalinity, chloride and ammonia, even though the moisture content has reduced considerably. Similarly the 15 m level emulates that at the end of the wet season, but with a reduction in water content

Generally there appears to be very little vertical movement of moisture through the profile and the large reduction in moisture content would indicate that there is possible lateral movement of moisture into the fill.

3.6.2 Linbro Park South Auger Hole.

3.6.2.1. End of wet season - The moisture content profile at the end of the wet season extends above 60% (i.e. the field capacity for household wastes) at the 3 m, 5 m and 13 m levels, indicating the presence of excess water available for leachate generation. Peak concentrations of all the solutes appear at the 6 m level, the point of lowest pH (6,7). It would thus appear that leachate is backing up in the refuse between 3 m and 6 m with the layer of soil at 6,3 m slowing further percolation down the profile.

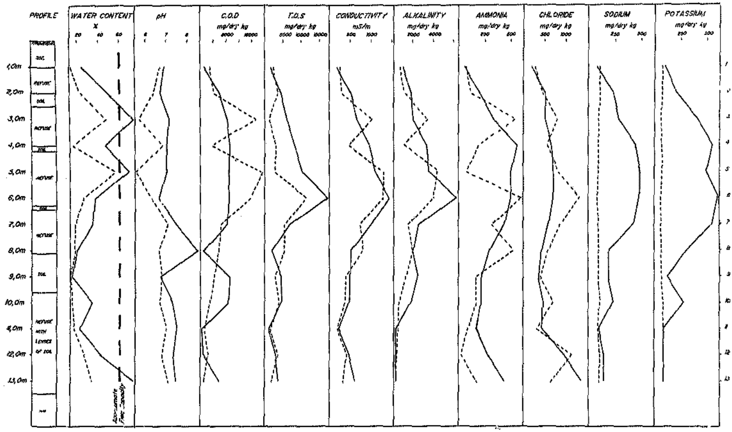


FIGURE 3.16(b) LINBRO PARK SOUTH AUGER HOLE

——— end of wet season (Jun 1988)

- - - - end of dry season (Nov 1988)

The landfill at this point was also constructed in two stages, the bottom stage up to the top of the soil layer at 8,1 m from 1970 to 1976, and the top stage in 1985 and 1986. At the 8 m level pH is highest (8,5) and corresponds to a large drop in COD *concentration*.

The lower level shows contamination at 13 metres, with high concentrations of COD, chloride and ammonia. The water content at this point is above the field capacity for domestic waste and indicates a small buildup of leachate at the base of the fill.

3.6.2.2 End of dry season - Apart from sodium and potassium the profile at the end of the dry season is very similar to that at the end of the wet season. However the total moisture in the profile has reduced by 33,5%. Observation of the moisture content profile shows that it has dried fairly consistently over the depth thus indicating that the moisture is not moving vertically but possibly seeping laterally into the landfill.

The pH has generally reduced to below neutral for the whole profile with very low pH's of 5,7 and 5,5 at 3m and 5 m respectively. This corresponds to high values of conductivity and alkalinity and very high COD's at these points. The indication is that the top seven metres of the landfill are only in the acid phase of decomposition.

Concentrations of all the parameters are lower at the 13 m level and the moisture content has reduced to well below the field capacity thus tending to show that there is not a build up of leachate at the base of the fill as shown up at the wet season.

3.6.3 Comparison of the two holes

The two holes are situated approximately 250m apart, but display widely varying characteristics. From observations on site the north hole's steel casing displayed no evidence of corrosion whereas the south hole's casing is covered in rust. The south hole also has a white fungus growth on the surface of the refuse which is absent in the north hole. On opening the holes there is evidence of a great deal of condensation on the steelwork and the sidewalls, possibly attributable to water vapour in the gases.

Surface water appears to have ponded in the area of the north hole but not in the south. This fact could account for the lower reduction in moisture in the north hole at the end of the dry season compared to the south hole. The holes could be the paths of least resistance (permeability), which attract a flow of moisture towards themselves, and could explain any lateral movement of moisture in the profile

In general the solute (or leachate) front appears to have reached a level about 5 to 6m below the surface in three years. The change of season affects the moisture in the profile. Movement of

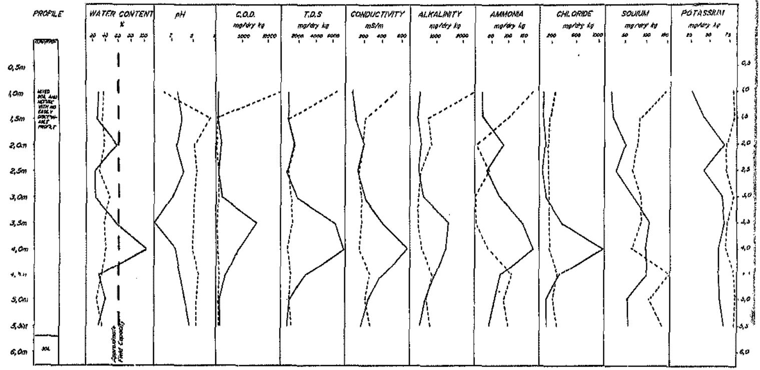


FIGURE 3.16(c) COASTAL PARK AUGER HOLE

.... end of dry season (May 1988)

———— end of wet season (Oct 1988)

the solute front is fairly static, less concentrated after the dry periods with no direct evidence of where the moisture is going to.

3.6.4 Coastal Park Auger Hole

3.6.4.1 End of dry season - The profile clearly shows a large peak concentration in nearly every parameter within the top metre and thereafter the profile does not appear to be chemically or biologically active.

The natural pH of the Coastal Park soil is 8,3 so the initial value of 6,7 together with a high COD is indicative of the onset of acid phase degradation. At no point in the profile is the moisture content near that at field capacity. Being the end of the dry season it is possible that solutes have moved upwards in the profile due to an evaporation gradient.

3.6.4.2 End of wet season - The moisture content in the profile over the wet season has increased by 15,5%. At 4 m the moisture content is well above field capacity and the moisture contents at 2 m and 3,5 m are almost at field capacity.

In general the pH has reduced over the entire profile, the low of 6,2 at 3,5 m and high COD at the same level indicating a leachate front at this point. Chloride, ammonia, conductivity and TDS concentrations peak at the four metre level.

The profile very neatly shows up the movement of a solute (or leachate) front from 1 m down to 4 m over the wet season but does not enable one to see whether the solutes move upwards during a dry season. It would be worthwhile analysing one more set of samples at the end of the dry season in 1989.

3.7 Sample extraction and Analysis (Unsaturated zone soil)

A grid of holes at Linbro Park, were excavated to a depth of 3m, starting at the landfill toe and moving away from the landfill, as shown in figure 3.15. A similar grid of holes were excavated at the Waterval landfill for comparisons. Samples of the soil were taken at 0,5m depth intervals and sealed in plastic bags. The grid was designed to obtain a picture of any contaminant migration in the horizontal and vertical directions in the near surface unsaturated zone.

Extraction of a liquor for analysis was done in the same way as that for refuse (described in Appendix G). It was then analysed for pH, COD, TDS, Alkalinity, ammonia, chloride, sulphate, sodium and potassium by a Commercial Laboratory. The moisture content of the soil was also calculated by oven drying. It should be stressed here that units used (i.e. mg/dry kg) are comparative thus enabling a comparison of the various soils treated in exactly the same way. The values are not absolute and can thus not be compared to a 'typical' leachate for example.

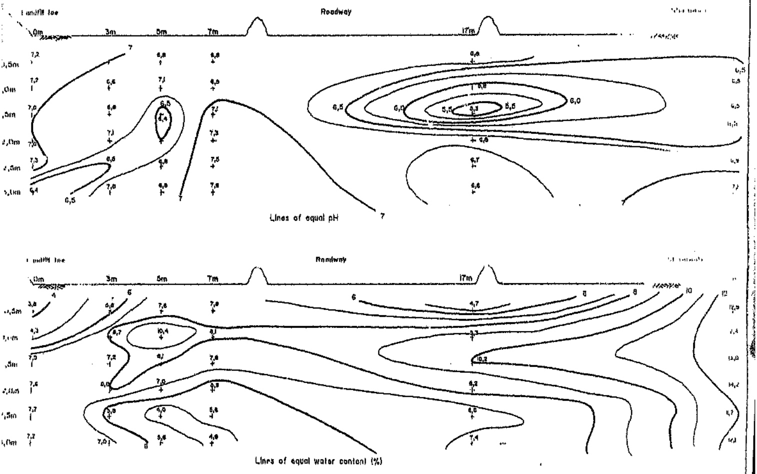


FIGURE 3.17 a LINBRO PARK UNSATURATED ZONE

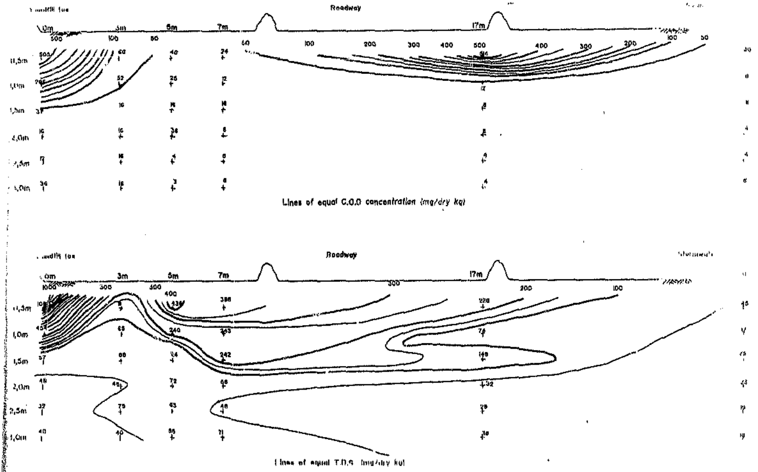


FIGURE 3.17 b LINBRO PARK UNSATURATED ZONE

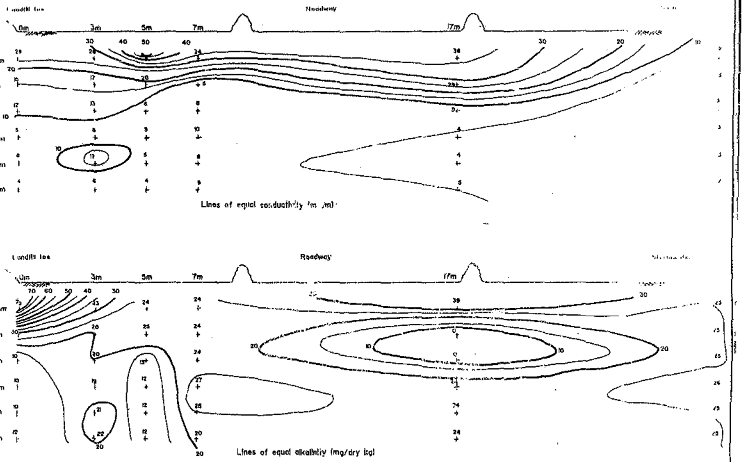


FIGURE 3.17 c LINBRO PARK UNSATURATED ZONE

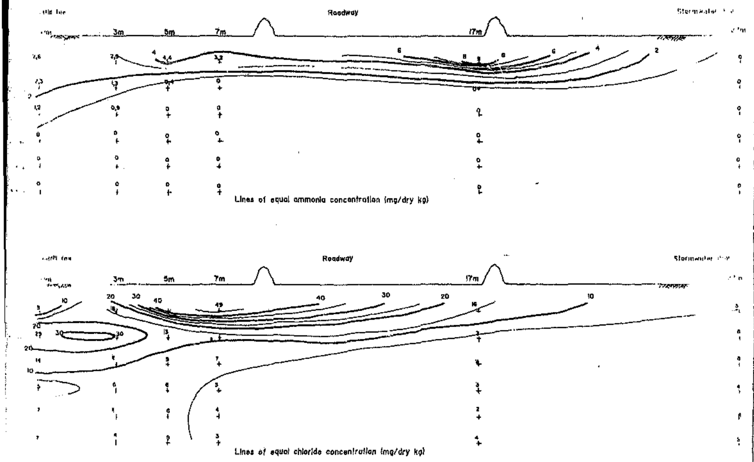


FIGURE 3.17 d LINBRO PARK UNSATURATED ZONE

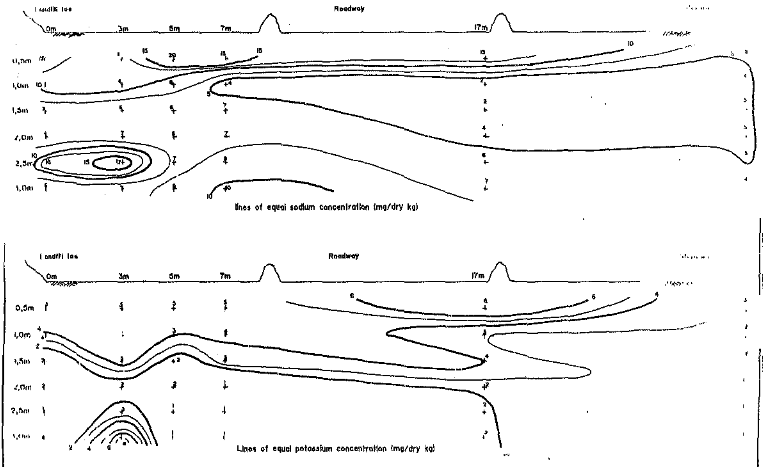


FIGURE 3.17 e LINBRO PARK UNSATURATED ZONE

Values from the analysis were then plotted in lines of equal concentration as shown in figures 3.17 (a) to (j) and are discussed below.

3.7.1 Linbro Park unsaturated zone profile

There appear to be four sources of contamination in the profile of holes :

a) Percolation is occurring below the toe of the landfill and moving away from the toe. The contaminants are rapidly attentuated (within 1,5 m vertically and 3 m horizontally), and the percolation is very small as evidenced by the low water contents of the soil. Contamination could be due to surface washoff by rainfall and seepage at the toe of the fill or due to fissures in the waste which allows the passage of a contaminated liquid to the base soil before the fill has reached its field capacity.

The samples were taken in July, half way into the dry season, and the horizontal movement could be partly due to the suction caused by evaporation of moisture in the top layers of soil.

b) Between five and seven metres from the toe of the landfill there is a source of high salt contamination (high conductivity, TDS, chlorides and sodium).

The causes for this contamination could either be surface washoff from the landfill slope or spillage of refuse by vehicles (the road is about 2 m away).

c) Seventeen metres from the landfill toe, at the edge of the road, there is a source of biological contamination (lower salts, but higher COD and low pH). This source of contamination is remote from the landfill and could have been caused by contaminated soil being graded onto the road or refuse spillage by vehicles.

d) Three metres from the landfill toe and at a depth of 2,5 m there is a slug of high salt concentration (Na, Cl and K). At 2,5 m deep it is unlikely that this was caused by surface contamination as it does not leave a trail, but can possibly be attributed to a pocket of soil with a high natural salt content.

To summarize the different parameters have been analysed seperately.

a) pH - The natural soil pH is neutral to slightly acidic. The profile shows a slightly raised pH (7,2) just below the toe of the fill and a depressed pH (5,3) seventeen metres from the toe, at the edge of the road.

b) Mositure content - *The moisture* content throughout the *profile is generally* low apart from a value of 14,2% in the soil below the stormwater channel, which is approaching the field capacity of 15%. At the toe of the fill the moisture content is its lowest at 3,8%, (just above the wilting point), which indicates that moisture in the profile comes from surface infiltration and not from the fill. Elevated *moisture contents* (above 10%) are noted at 5 m and at 17 m.

c) *Chemical* Oxygen Demand - The COD values at the toe of the landfill are high (505 mg/kg) but reduce rapidly to below 50 mg/kg within 1,5 m vertically and 3 m horizontally. A second set of elevated COD values appears at 17 m supporting a contamination trend picked up by pH and moisture content.

d) Total Dissolved Solids - *Below the landfill* toe the pattern for TDS is very *similar* to *that for* COD with a high of 1060 mg/kg *reducing* to less than 100 mg/kh within 1,5 m vertically and 3 m horizontally. TDS at the 17m mark however does not support the contamination trends as shown up by pH and COD, possibly due to the fact that the contamination is mainly biological and would not produce the large amount of salts normally associated with a high TDS.

e) *Alkalinity* - Alkalinity figures again support the *contamination* trend from the toe of the landfill as shown up by pH, COD and TDS. However the contaminant source at 17 m shows an alkalinity of zero which could be linked to the depressed pH's (5.8 and 5,3) at these points, thus *supporting the trend.*

f) Conductivity - The conductivity contours are almost parallel to the ground surface, reducing in concentration with depth. The peak conductivity (51 mS/m) is at 5 m. One *would expect* the *conductivity contours* to be similar to those for TDS (i.e. a measure of the salt content of the solution), however in this case it may be possible that the high TD [illegible] at the toe of the fill are due mainly to organic m[illegible] *dissolved gases,* that not *affecting* the *conductivity* very [illegible]

g) Ammonia - The ammonia contours are approximately parallel to the ground surface, rapidly reducing in concentration in the *top* metre of soil. *This is to be* expected in natural soil as NH_4 concentration decreases rapidly, converting to NO_3, in aerobic conditions. The ammonia values are pleasing in that they show that the soil profile is almost free of contamination.

h) Chloride - Chloride concentration is highest between 5 and 7 m from the landfill toe indicating a contaminant source at this point. The chloride value below the landfill toe (9,3 mg/kg) is low, but if it is disregarded *as an error,* a trend of *contamination* supporting that of COD, TDS and conductivity becomes evident.

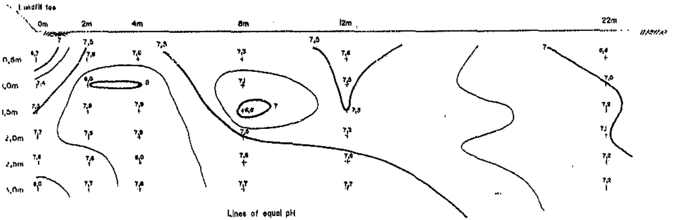
i) Sodium - *Sodium concentration* is highest (20 mg/Kg) at 5 m from the *landfill* toe and in general reduces with depth through *the profile. However* there is a high concentration slug of *sodium* at a depth of 2,5 m up to 3 m from the landfill toe. *There* is a similar slug of higher concentration chloride at this point indicating possible salt contamination.

j) Potassium - Potassium shows a general reduction in concentration with depth apart from a slug 3 m from the landfill toe at a depth of 2,5 to 3 m. This corresponds to the sodium and chloride slugs found in the same area.

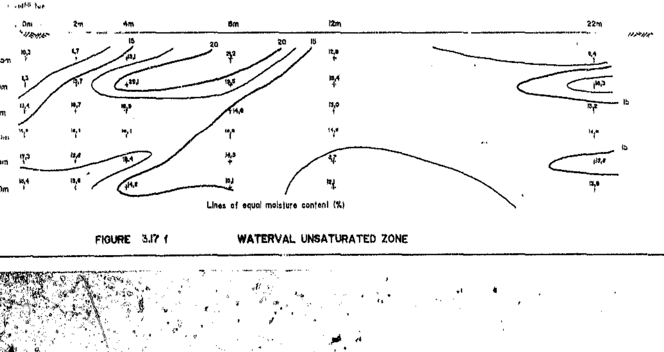
In general the contamination below the fill is most likely *due* to washoff by rainfall and/or direct drainage paths *(fissures)* through the waste to the base of the *landfill. The low moisture* directly below the fill as *compared* to the *higher* moisture elsewhere would indicate that the *fill is not* at its field capacity and is thus not *allowing leachate* to percolate through its base.

3.7.2 *Waterval unsaturated* zone profile.

It *should* be noted at the outset that evidence of fill using *different* soils and rubble was found in the 12 m and 22 m *profiles.* It was attempted to sample only the natural clay for the area but this factor should be considered when examining the results of the analysis and drawing conclusions.

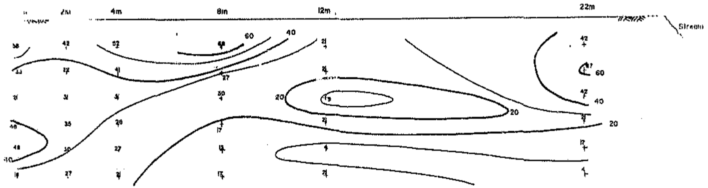


Lines of equal pH

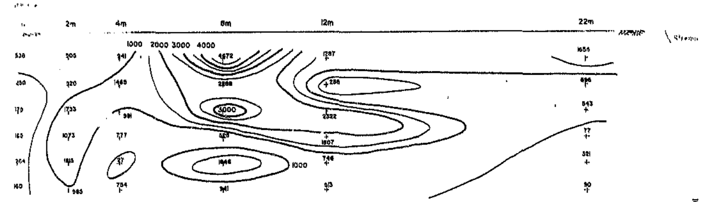


Lines of equal moisture content (%)

FIGURE 3.17 f WATERVAL UNSATURATED ZONE

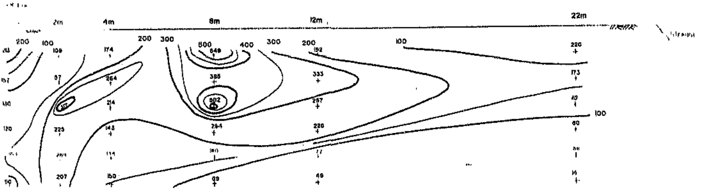


Lines of equal C.O.D (mg/dry kg)

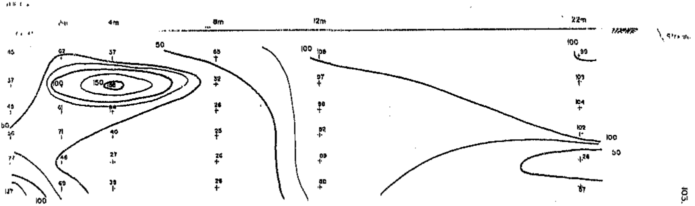


Lines of equal T.D.S (mg/dry kg)

FIGURE 3.17 g WATERVAL UNSATURATED ZONE



Lines of equal conductivity (mS/m)



Lines of equal alkalinity (mg/dry kg)

FIGURE 3.17 h WATERVAL UNSATURATED ZONE

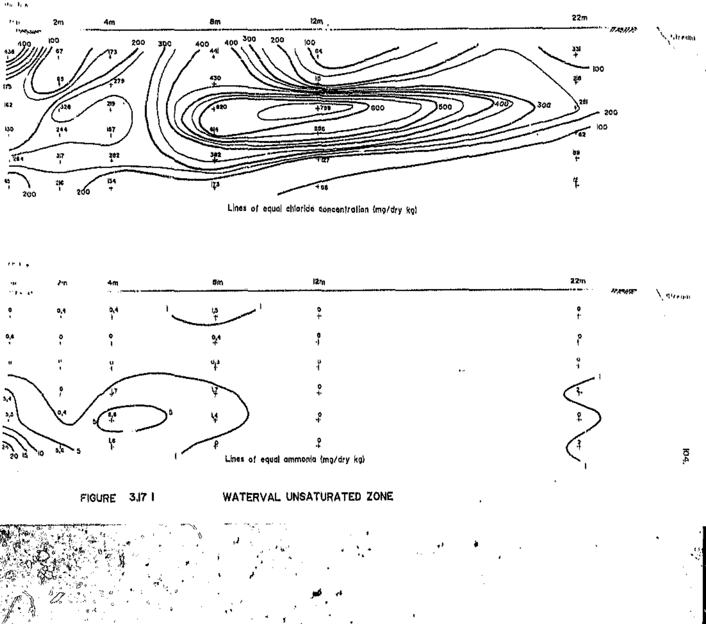
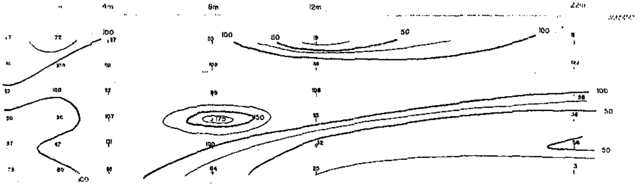
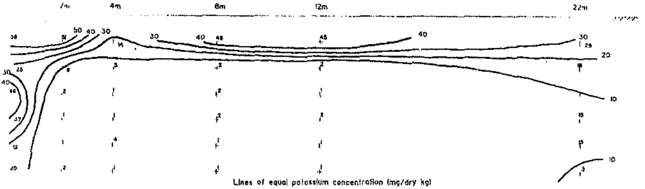


FIGURE 3.17 I WATERVAL UNSATURATED ZONE



Lines of equal sodium concentration (mg/dry kg)



Lines of equal potassium concentration (mg/dry kg)

FIGURE 3.17 j WATERVAL UNSATURATED ZONE

One would expect fairly high salt contents in the profile due to the nautral salts present in the clay (see table 3.7). The area sampled was also in a vlei, where salts would be concentrated by natural processes. Without background values it would thus make it difficult to draw conclusions from the salt and TDS profiles. An indicator of biological contamination is COD where all the values are low. At a glance it would appear that there is very little contamination of this unsaturated zone profile.

However under close scrutiny there are indicators of potential contaminant movement. Chloride and potassium and, to a lesser extent, conductivity and COD show signs of a plume emerging at the toe of the fill. More noticeable though is the sign of plume moving lateraly, 2 to 3 m below the toe, as shown up markedly by ammonia and, to a lesser extent, by potassium, chloride, conductivity, alkalinity and COD. If the source of contamination is attributed to the landfill, the mechanism could be due to a less permeable layer of soil restricting the downward percolation of leachate which then migrates horizontally.

The different parameters have been analysed seperatly below :

a) pH - the pH is generally above neutral with a high of 8,1 four metres from the toe of the fill and a minimum of 6,7 at the toe.

b) Moisture content - the soil moisture is lowest at the toe of the fill (10,3%) and reaches a maximum of 22,1% about four metres from the toe. This can be attributed to surface infiltration.

c) Chemical Oxygen Demand - the COD values are all relatively low (below 68 mg/kg).

d) Total Dissolved Solids - TDS is generally quite high through the profile with the lowest values occurring directly below the landfill toe (160 mg/kg). The highest values occur near the surface 8 m from the landfill toe (46[illegible] mg/kg).

e) Alkalinity - Alkalinity shows an interesting trend with a high value (137 mg/kg) directly below the landfill toe at a depth of 3 m. The concentrations reduce upwards and away from the toe, apart from a single peak of 158 mg/kg four metres from the toe. This corresponds to the high pH at that point.

f) Conductivity - Conductivity shows a similar pattern to the TDS contours, as can be expected due to the high salt concentrations in the soil which increase TDS and conductivity.

g) Ammonia - Ammonia picks up the trend shown in alkalinity with a high of 24 mg/kg at a depth of 3 m below the landfill toe, decreasing in concentration upwards and away from the toe. This is a clear indication of the appearance of contamination at the 3 m level.

h) Chloride - Chloride concentrations are fairly high (436 mg/kg) directly below the toe of the fill, but reduce rapidly and then show themselves in a plume 8 m from the toe, with a peak concentration of 620 mg/kg.

i) Sodium - Sodium concentrations are fairly evenly spread throughout the profile and show only one high peak 8 m from the landfill toe.

j) Potassium - Potassium concentrations are high at the landfill toe but reduce rapidly. They then show support for the trend picked up by ammonia and alkalinity of a sideways movement of contamination about 2 m below the landfill toe.

In general it would appear that there is a surface contamination at 8m, not attributable to the landfill, and indications of a sieways moving plume of contamination between 2 and 3 metres below the base of the fill. It is suggested that this plume be observed closely for evidence of attentuation or pollution.

3.8 Test Lysimeters

Two lined test cells or lysimeters were built on site in March 1988 to confirm any prediction of leachate generation (see figure 3.16). Each cell measures 9m wide at its base, 18m wide at the

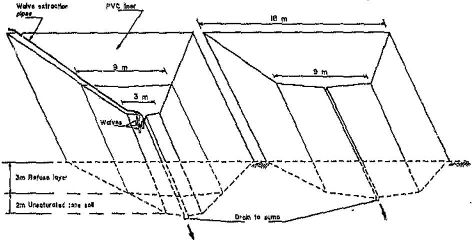


FIGURE 3,18 TEST CELLS AT LINBRO PARK

top and is 3m deep. The cells are lined with a 500 micron PVC lining to contain and drain any leachate produced. Cell (1) has a 2m unsaturated zone above the liner to simulate the usual unsaturated zone, while cell (2) has only a 300mm protective layer of soil between the waste and the lining. Each cell contains a collection pipe contained in a drainage trench with 15mm gravel, which drains into two separate 210 litre sumps for collection of the leachate. Cell (1) in addition has three Walves (Wick Assisted Lysimeters with Vacuum Extraction), developed by Ball and Blight [86], installed in the unsaturated zone at 0,5m, 1,0m and 1,5m below the refuse. The walves are intended to extract liquid from the unsaturated zone by exerting a negative pressure in a cone which leads into a collection tube.

Each cell was filled with refuse on consecutive days, compacted using a 27t landfill compactor, and then covered with 500mm of soil.

To date there has been no percolation in either of the two test cells. No samples have been extracted from the walves and it is still uncertain if they are going to function or not. However zero outflow from cell (2) into the sump confirms the point that no percolation has taken place through the base.

To accelerate conditions, as from 1 June 1988, the total pan evaporation minus rainfall for the previous month was placed on cell (1) using a garden sprinkler. It was attempted to do this over the period of one day without allowing any runoff to occur. In this way, conditions in the cell would approximate those in a zero water deficit area.

A water balance has been calculated on a daily basis for the two cells. Initial conditions are a refuse density of 967kg/m^3 in cell (1) and 1010kg/m^3 in cell (2), calc lated by surveying the areas before and after refuse placement and taking masses from the site weighbridge. The initial moisture content of the refuse can be assumed to be 20%. The top surface has a slope of 1 : 24 and the face of 1 : 6. The soil is bare of any vegetation and meteorological data is measured daily on site. The 100mm soil moisture retention tables in appendix B have been used.

At the end of November 1988 cell (1) had a total of 216.3mm percolation (accelerated conditions), and cell (2) had zero percolation. The cover for cell (2) was however close to its field capacity, indicating that percolation would take place if the normal summer rains continue.

The total moisture holding capacity for the two test cells was also calculated. Cell (1) would be able to hold 1564mm of percolation before producing leachate, and cell (2) can hold 1233mm. At an average accelerated rate of percolation into cell (1) of 27mm per month, it is estimated that leachate would begin to fill the sump in 58 months (i.e. January 1992).

4. DISCUSSION OF RESULTS

4.1 Predicted *leachate generation* at Linbro Park.

At the two profiles through Linbro Park under consideration, the waste was deposited in two stages. The top eight metres were filled during the years of 1985 and 1986, while the lower stage was filled between 1970 and 1976. For this reason the water balance for the two sections needs to be *considered seperately.*

The figure for *predicted percolation* is taken from section 3.3.1 and *is a mean* plus standard deviation of all the water balances done for the area, thus including a certain factor of safety. Calculations are shown in Appendix I.

According to this theory moisture in both the north and the south holes should be entering the second refuse *layer (about 2,7m* below the surface); with a *total amount of* additional water in the profile of *3240mm. From* the 4882mm water holding capacity in the *north hole* and the 5156mm water holding capacity in the south hole, it is predicted that the landfill will reach field capacity in :

12 years for the north hole (i.e. 2001 a.d.) and
14 years for the south hole (i.e. 2003 a.d.).

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According to this theory moisture in both the north and the south holes should be entering the second refuse layer (about 2,7m below the surface); with a total amount of additional water in the profile of 3240mm. From the 4882mm water holding capacity in the north hole and the 5156mm water holding capacity in the south hole, it is predicted that the landfill will reach field capacity in :

12 years for the north hole (i.e. 2001 a.d.) and
14 years for the south hole (i.e. 2003 a.d.).

After such time the rate of leachate generation would be at 136mm per year.

4.2 Measurements of leachate generation at Linbro Park

Moisture contents have been taken throughout the profiles in the north and south auger holes. Using these moisture contents and assuming initial conditions for soil and refuse, any additional moisture in the holes can be calculated as shown in Appendix J.

From these calculations it appears that the extra moisture (which leads to leachate production) is:

i) 2603mm in the north hole at the end of the wet season, but only 1734mm at the end of the dry season, and

ii) 3584mm in the south hole at the end of the wet season,but only 1767mm at the end of the dry season.

This can be compared with the predicted extra moisture in section 4.1 of 3240mm.

4.3 Comparison of results

If one takes the actual extra moisture at the end of the wet season (i.e. the worst case) it would appear that actual leachate generation is at least 20% less than predicted in the north hole and 10% greater than predicted in the south hole. The predicted leachate generation was based on the mean plus standard deviation of an arbitrary number of percolation calculations and correlates quite closely to that measured at the end of the wet season.

From table 3.5 the *figures for* calculating percolation on a daily *basis (i.e.* 133mm for 1m cover and 264mm for 200mm cover) are fairly close to the mean used in the prediction. However a daily calculation of water balance becomes very cumbersome. The weekly period of calculation does however give figures 68 and 59% of those calculated on a daily basis (i.e. 92mm and *179mm*). Calculation of percolation on a weekly *basis using a factor of* safety of 1,5 would *thus appear to produce* a reasonable estimate of *leachate production.*

The end of the dry season figures of actual extra moisture are about 46% less than the predicted percolation in both holes. This fact tends to emphasize that an accurate prediction of leachate generation is impossible, but that a reasonably safe "ballpark" figure can be used based on the worst *case* at the end of the wet season, as *shown above. An* understanding of the various *factors affecting this figure* will give a better valued *judgement of* its validity:

i) initial conditions assume a dry soil (3%), and an initial refuse moisture of 20%. The soil moisture will be higher during the wet season and *initial refuse moisture* can be extremely variable (from paper, at close to *0%, to sludge,* which may be greater than 100%), depending on *refuse type,* storage and weather conditions.

ii) In measuring percolation, there were a number of *layers of* mixed soil and refuse for which initial conditions have been assumed for a ratio of 1 soil to 4 refuse.

iii) The profile as shown may not be 100% accurate due to the *mixing* of soil and refuse and the "blurring" of the two contact *layers.* The nature of the refuse cell construction (shown in *figure 3.1) means* that the hole may have been augered through a *diagonal closed face* in places, which would account for those parts of *the profile where refuse* appears as a narrow layer less than one metre *thick.*

iv) The hole itself may be a *direct line for drainage* of water, thus making the profile wetter than *is normally the case.* The large reduction in moisture at the end of the *dry season could* be due to excess moisture from the hole walls seeping *laterally into* the fill under a suction gradient caused by the drier *materials* within the landfill. Samples are only taken from the side walls of the holes and thus small lateral movements of moisture would affect the analysis of the sample.

v) *Operational* problems, discussed in section 3.3.1, such as landfill settlement, surface ponding, surface cracks and surface erosion will greatly affect the percolation of water into the wastes.

vi) Weather conditions during deposition. Rain falling onto open waste will soak in with very little runoff taking place. This moisture is likely to be sealed into the waste after covering with the daily soil cover.

vii) Factors in the water balance such as evapotranspiration and runoff are very difficult to measure or calculate accurately and yet these are crucial to the calculation of leachate generation.

viii) Water balance for future sanitary landfills will be calculated from past records and yet from year to year and even from day to day the variables are quite different. Linbro Park received 442mm of rainfall in 1984 and 1019mm of rainfall in 1987. In one day in October 1985 it received 110mm rainfall (14% of the total rain for the year). The Coastal Park area received 321 mm of rainfall in 1973 and 751mm of rainfall in 1977. Quite clearly there are times when there will be zero percolation in a year and times when percolation will exceed predictions by a large quantity.

ix) A water balance is usually calculated for a completed section of the landfill. However, a water balance calculation should be performed at each level during filling and added to the landfill settlement, surface ponding, surface cracks and surface erosion will greatly affect the percolation of water into the wastes.

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ix) A water balance is usually calculated for a completed section of the landfill. However, a water balance calculation should be performed at each level during filling and added to the completed water balance.

x) Due to fissures and other direct paths through the waste and soil a certain amount of water will not be held in the waste "sponge" but will produce leachate at the base of the fill. This will account for the build up of moisture in the bottom layer of the auger holes at the end of the wet season.

4.4 Comparisons at Coastal Park

The profile of the auger hole at Coastal Park is a mixture of refuse and sand to a depth of six metres. Assuming the mix is 200mm of soil for two metres of refuse, this will produce a combined dry unit weight of 870 kg/m^3. A figure of field capacity for the sand has not been measured, but is assumed to be similar to Linbro Park at 15% (as supported by Fenn et al.[47] in their table 2 of soil moistures).

Total water in the profile is [illegible] 1825mm after the dry season and 2108mm after the wet season (i.e. from May 1985 to October 1988). Initial conditions assume a total of 1180mm of moisture in the profile. Therefore additional moisture is 645mm and 928mm after the dry and wet seasons respectively. This gives a total percolation of 283mm. Predicted percolation from the monthly water balance (see appendix H) is 208mm per year taken as a mean over 20 years.

Records kept on site show that precipitation during this period was 465mm and leachate flowing through the base was 18mm. Pan evaporation over the period was 333,7mm as measured at D.F.Malan Airport. Working on differences, the actual evaporation and runoff during this period = 465-18-283

= 153mm.

Assuming zero runoff, due to the nature of the cover soil, and negligible transpiration, the measured figure for actual evaporation is about half that of pan evaporation.

4.5 Leachate control measures

Notwithstanding all the theory of how leachate is produced, and in what quantities, it is ultimately the landfill operator who can actually control the levels of leachate production. A poorly run landfill in a water deficit area can produce more leachate than a well run site in a water surplus area. The various operational factors that affect the production of leachate are listed below:

i) The landfill should never be sited with its base below the level of the ground water table.

ii) Waste should be deposited on a dry area with the deposition surface sloping away from the face. Any precipitation will then run off and will not dam up in the area of deposition.

iii) Daily soil cover of the waste is essential, so that runoff will be increased and infiltration reduced. A soil cover of low permeability heavy clay is theoretically best for reducing infiltration and increasing runoff, but will crack when it dries out, and will cause problems for vehicles in wet and slippery conditions. In this case a thin layer of gravel, old tarmac or building rubble can be placed on top of the clay as a driving surface for vehicles, which will not affect infiltration and will retain moisture in the clay, thus preventing it from drying out. A well graded sandy loam such as the soil at Linbro Park is also good as it has a relatively low permeability but retains a good driving surface and does not crack. It is however prone to erosion and so requires constant maintenance.

iv) The final cover may be placed in a variety of ways:

a) Top soil placed directly over the wastes. This will give any precipitation easy access to the wastes and leachate production will increase. Landfill gas will be well vented naturally through the cover soil.

b) A layer of soil cover compacted slightly wet of optimum (for lowest permeability at the highest density), before covering with top soil. Care should be taken to ensure that the grades will effectively drain away any excess water. Gas should be able to vent itself naturally.

c) A synthetic liner (eg. PVC or HDPE) placed below the layer of top soil. This will effectively seal the wastes from any percolation from the time of placement. Care must be taken to control drainage on top of the liner, and to monitor any settlement of landfill which may cause tears and reduce the integrity of the liner. Gas vents will be necessary to prevent a dangerous build up of gases below the liner.

d) A clay sealing layer can be placed below the final layer of top soil. This would be similar to a synthetic liner in that drainage and gas venting will be required, but differential settlement would not be as great a problem due to the natural self-healing capabilities of clay. However the clay must be well covered so that cracking does not occur due to drying out.

vi) Aftercare of the final cover is very important. Planting of vegetation is desirable in that it will increase evapotranspiration and reduce erosion, but has the adverse effect of reducing runoff. Differential settlement of the landfill will occur causing areas of depression where ponding will take place. Those should be filled regularly, and the covering and repair of surface cracks and erosion channels should be done as soon as they occur.

vii) An essential component of leachate management is site drainage. Excess run on from the surrounding areas should be eliminated, and any precipitation that falls onto the site that is available for runoff must in fact run off.

viii) The area of operation should be contained to the smallest practicable, so that there is only a small catchment area for the precipitation to fall on.

ix) Irrigation is often carried out after closure due to a site end use as a sports ground or a park. If at all possible an end use should be chosen such that little or no irrigation is required for its maintenance.

4.6 Recommendations to improve accuracy of leachate prediction and detection

More accurate predictions of leachate generation are possible with more accurate data. Records should be kept at landfill sites of details such as refuse cell heights, dates of deposition, in situ densities, moisture and amount of cover used. Meteorological data such as rainfall and evaporation should be recorded. A lysimeter filled with soil, using either soil moisture detection devices or mounted on a mass measuring scale (for a mass balance) would be a more preferable and accurate instrument to measure actual soil evaporation. Runoff could also be measured if the drainage system for the site allows it. With these records a prediction of leachate production using the water balance method could be done with more confidence. There is a method to measure the accuracy of such a prediction, by installing early warning devices so that first appearance of excess moisture is known.

Instrumentation is available for installing below a site before operations commence. This is ideally for attenuation sites but containment sites can be instrumented where early detection of a leak is required. The sensors installed will most usually be able to detect pore water, water content, soil suction or soil temperature.

The first two detection instruments are related. The pressure vacuum lysimeter, consisting of a porous cup with a vacuum applied to the inside, will suck water from the pores of the soil, and bring the sample to the ground surface through tubing by using air pressure or a vacuum. The lysimeter however does not work in relatively dry soils (83). The wick assisted lysimeter with vacuum extraction, or Walve, developed by Ball and Blight, works on a similar basis. A cone of fine grained filter material catches the liquid which drips down a wick into the catching receptacle. The Walve has not however been proven at this stage.

There are a number of soil moisture sensors. The simplest and least expensive would be the resistance block made from gypsum, nylon or fibreglass. The block is porous and absorbs water from the surrounding soil thus producing a change in its electrical resistance. Hundreds of blocks could be buried below the landfill to provide a well spread grid for excess moisture detection.

Neutron moisture probes are more expensive and more sophisticated. A grid of horizontal access tubes can be placed below the landfill and the probe passed through to give a continuous log of moisture in the soil adjacent to the tube. An advantage of the neutron probe is that it can be serviced and calibrated above ground, resulting in more reliable results.

Heat dissipation sensors measure the rate of heat dissipation around a probe, which normally varies with soil moisture content. The sensors are inexpensive and durable and can be used in a grid similar to the resistance blocks. Capacitance sensors monitor the soils dielectric constant which varies according to its water content. Finally earth resistivity can be measured with metallic plates or rods buried in the ground. The resistance varies with moisture in the soil and the electrolyte concentration of the soil water.

Other detection devices measure the actual soil suction. Tensiometers measure suction of relatively moist soils but are expensive and must be filled with a liquid, thus requiring regular servicing. Thermocouple psychrometers can monitor changes in the suction of a relatively dry soil and would be better suited to landfill leachate detection.

A relatively inexpensive system of sensors of more than one type can be developed which would give an early warning of the start of a leachate plume. If this is tied into a system with accurate records, and a confident water balance calculation, it could provide invaluable information for other landfill operators in the country.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions :

The aim of the investigation was to find a reasonably accurate method for predicting the flow of leachate in a landfill. This initially involved a study of the different parameters in the water balance. Rainfall proved to be the simplest to measure, while evapotranspiration, runoff and infiltration are a lot more complex. The method involves a number of broad assumptions with little confidence in the final accuracy of the results.

As a basis for design it is recommended that a weekly water balance should be calculated including a factor of safety of 1,5 in the final percolation figure. This is based on a potential evapotranspiration of 0,7 x pan evaporation and using a runoff coefficient according to slope and soil type.

A double check on predicted percolation was available in the form of large diameter holes augered through the landfill. These were sampled at regular intervals and analysed for a number of parameters to give an approximate measurement of the flow of leachate through the fill. Again the method can be subject to errors depending on the composition of the sample taken, but it provides a clearer indication of the extent of migration, and relates fairly closely to the water balance prediction as recommended above. It also shows very clearly the changes in moisture in the landfill from season to season.

Testing for the geotechnical properties of refuse and soil in the laboratory again showed up the widely varying behaviours one can expect from waste materials. A figure for field capacity, permeability or specific gravity can vary for composition, state of decomposition and density. The important point being brought to light is that these properties are quantifiable, and the more tests done to quantify them, the more confident a designer will become in using the figures.

Sampling of soil in the near surface unsaturated zone proved to be very interesting. It produces a tell tale history of occurrences of surface contamination from various sources, it shows an indication of the attenuation mechanisms at work in the soil and it can highlight the emergence of a possible leachate front. It also shows that contaminant migration is not only vertical but can be in the horizontal direction as well.

In conclusion this investigation has pointed out the necessity to do a detailed (at least weekly) water balance calculation, with an understanding of the shortcomings of the method. It showed that geotechnical properties of refuse, even if widely varying, can be quantified within certain limits. Further, leachate production is a function of infiltration beyond the field relates fairly closely to the water balance prediction as recommended above. It also shows very clearly the changes in moisture in the landfill from season to season.

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In conclusion this investigation has pointed out the necessity to do a detailed (at least weekly) water balance calculation, with an understanding of the shortcomings of the method. It showed that geotechnical properties of refuse, even if widely varying, can be quantified within certain limits. Further, leachate production is a function of infiltration beyond the field capacity of the fill. Thus the landfill designer and operator should promote surface runoff and evapotranspiration wherever and whenever possible.

5.2 Recommendations for future research

The auger holes at Linbro Park and Coastal Park have produced interesting and useful results. There is however no conclusive evidence as to where the water is going, and it is suggested that these holes be resampled at least at the end of the next wet and dry seasons to establish a trend.

More extensive tests are required to establish the geotechnical properties of the different types of refuse, and to confirm figures measured in this report.

Research is required into the suitability of the different types of monitoring instrumentation to South African conditions.

APPENDIX A : AMERICAN SOIL CONSERVATION SERVICE RUNOFF ESTIMATION

Wanielista [41] describes a method for estimating stormwater runoff as developed by the American Soil Conservation Service (SCS). In this system the slope of the surface is not considered but the excess rainfall (i.e. that amount that will not infiltrate) can be estimated and it is this excess rain that leads to runoff.

The SCS divided soils into hydrologic groups as shown in Table A1.

TABLE A1. HYDROLOGIC SOIL GROUPS

A - Lowest runoff Potential : Includes deep sands with very little silt and clay; also, deep, rapidly permeable gravel.

B - Moderately low runoff potential. Mostly sandy soils less deep and less aggregated than A, but the group as a whole has above average infiltration after thorough wetting.

C - Moderately high runoff potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than those of group D. Below average infiltration after saturation.

D – Highest runoff potential. Includes mostly clays of high swelling percentage, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface.

NOTE : A mixed designation i.e. B/D refers to drained/undrained natural situation.

The antecedent soil moisture condition affects infiltration into the soil and it is thus taken into account by assuming one of three antecedent moisture conditions as in Table A 2.

	Table A 2
CONDITION 1	*Soils are dry but not to the wilting point*
CONDITION 2	The average case
CONDITION 3	Heavy rainfall, or light rainfall with low temperatures, has occurred producing high runoff potential.

Runoff curve numbers (CN) can then be found from Tables A3, A4 or A5, depending on Land Use, and adjusted in Table A6 for antecedent moisture conditions.

The maximum storage of moisture at any time is then calculated by S where

$$S = 25400/CN - 254 \text{ (mm)}$$

and the rainfall excess available for runoff by Q where :

$$Q = (P - 0,2S)^2 / (P + 0,8S) \quad \text{if } P < 0,2S$$

$$\text{and } Q = 0 \quad \text{if } P >= 0,2S$$

where P = precipitation (mm).

Table A 3 : CN (moisture condition 2)

LAND USE	HYDROLOGIC SOIL GROUP			
	A	B	C	D
Cultivated land : without conservation	72	81	88	91
: with conservation	62	71	78	81
Pasture : Poor condition	68	79	86	89
: Good condition	39	61	74	80
Meadow	30	58	71	78
Wood or Forest : Thin stand, poor cover, no mulch	45	66	77	83
: Good cover	25	55	70	77

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Meadow	30	58	71	78
Wood or Forest : Thin stand, poor cover, no mulch	45	66	77	83
: Good cover	25	55	70	77

Open spaces : Good - grass on 75%					
or more		39	61	74	80
Fair - grass on 50%					
of area		49	69	79	84
Commercial and business areas					
(85% impervious)		89	92	94	95
Industrial district '72%					
impervious)		81	88	91	93
Residential :	Average %				
Average lot size	impervious				
1/8	65	77	85	90	92
1/4	38	61	75	83	87
1/3	30	57	72	81	86
1/2	25	54	70	80	85
1	20	51	68	79	84
Paved parking lots, roofs, drive-					
ways etc.		98	98	98	98
Roads : Paved, with curbs and					
stormwater drains		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89

Open spaces : Good - grass on 75% or more		39	61	74	80
Fair - grass on 50% of area		49	69	79	84
Commercial and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential : Average lot size	Average % impervious				
1/8	65	77	85	90	92
1/4	38	61	75	83	87
1/3	30	57	72	81	86
1/2	25	54	70	80	85
1	20	51	68	79	84
Paved parking lots, roofs, drive-ways etc.		98	98	98	98
Roads : Paved, with curbs and stormwater drains		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89

Table A 4 : CN Pervious Areas

(moisture condition 2)

LAND USE	HYDROLOGIC SOIL CLASS			
	A	B	C	D
Bare ground	77	86	91	94
Gardens or row crop	72	81	88	91
Good grass (cover greater than 75%	39	61	74	80
Fair grass (cover between 50 and 75%)	49	69	79	84
Poor grass (cover less than 50%)	68	79	86	89
Fair woods	36	60	73	79

Table A5 : CN - Impervious areas

(moisture condition 2)

% Impervious area	CN
100	98
90	97,5
80	97
70	96,5
60	96
55	95
50	94
45	93
40	92,5
35	91
30	91

Table A 6 : CN ADJUSTMENTS

CN - CONDITION 2	CONDITION 1	CONDITION, 3
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50

APPENDIX B : SOIL MOISTURE TABLES

Thornthwaite and Mather's soil moisture tables (73) are used for the prediction of evaporation from a soil at different stages of desiccation. A few of the tables can be found reproduced in tables B1 a to f.

In the tables : $PE = \Sigma I_{negative}$

$I = P - PET - R/OFF$

P = Precipitation

PET = Potential evapotranspiration

R/OFF = Runoff

TABLE BI (a)

SOIL MOISTURE RETENTION TABLE – 25 MM

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 25 MM.

PE	0	1	2	3	4	5	6	7	8	9
					Water Retained in Soil					
0	25	24	23	22	21	20	19	18	17	16
10	16	15	15	14	13	13	12	12	11	11
20	10	10	9	9	8	8	8	8	7	7
30	7	6	6	6	5	5	5	5	5	4
40	4	4	4	4	3	3	3	3	3	3
50	3	3	3	2	2	2	2	2	2	2
60	2	2	2	2	1	1	1	1	1	1
70	1	1	1	1	1	1	1	1	1	1
80	1	1	1	1	1	1	1	1	1	1
90	1	1	1	1						

TABLE B I (b)

SOIL MOISTURE RETENTION TABLE – 50 MM

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 50 MM.

PE	0	1	2	3	4	5	6	7	8	9
					Water Retained in Soil					
0	50	49	48	47	46	45	44	43	42	41
10	41	40	39	38	37	36	36	35	34	33
20	33	32	32	31	30	30	29	28	28	27
30	27	26	25	25	24	24	23	23	22	22
40	21	21	20	20	19	19	19	18	18	18
50	17	17	17	16	16	16	15	15	15	14
60	14	14	13	13	13	13	12	12	11	11
70	11	11	11	10	10	10	10	9	9	9
80	9	9	9	8	8	8	8	8	8	8
90	7	7	7	7	7	7	7	6	6	6
100	6	6	6	6	6	6	5	5	5	5
110	5	5	5	5	4	4	4	4	4	4
120	4	4	4	4	4	4	4	4	3	3
130	3	3	3	3	3	3	3	3	3	3
140	3	3	3	3	2	2	2	2	2	2
150	2	2	2	2	2	2	2	2	2	2
160	2	2	2	2	2	2	2	2	1	1
170	1	1	1	1	1	1	1	1	1	1
180	1	1	1	1	1	1	1	1	1	1
190	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1
210	1	1	1	1	1	1	1	1	1	1
220	1	1	1	1	1					

TABLE B I (c)

SOIL MOISTURE RETENTION TABLE - 75 MM

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 75 MM.

PE	0	1	2	3	4	5	6	7	8	9
					Water Retained in Soil					
0	75	74	73	72	71	70	69	68	67	66
10	65	64	63	62	61	60	59	56	58	57
20	57	56	55	54	53	53	52	51	51	50
30	50	49	48	47	46	46	45	45	44	44
40	43	43	42	41	40	40	39	39	38	38
50	38	37	36	36	35	35	35	34	34	33
60	33	33	32	31	31	31	30	30	29	29
70	28	28	28	27	27	27	28	26	25	25
80	25	24	24	23	23	23	23	22	22	22
90	22	21	21	21	20	20	20	20	19	19
100	19	19	18	18	18	18	17	17	17	17
110	16	16	16	16	15	15	15	15	15	14
120	14	14	14	14	13	13	13	13	13	13
130	12	12	12	12	12	12	11	11	11	11
140	11	11	11	10	10	10	10	10	10	10
150	10	10	9	9	9	9	9	9	9	8
160	8	8	8	8	8	8	8	8	7	7
170	7	7	7	7	7	7	7	7	6	6
180	6	6	6	6	6	6	6	6	6	6
190	6	6	5	5	5	5	5	5	5	5
200	5	5	5	4	4	4	4	4	4	4
210	4	4	4	4	4	4	4	4	4	4
220	4	4	3	3	3	3	3	3	3	3
230	3	3	3	3	3	3	3	3	3	3
240	3	3	3	3	3	3	3	3	3	3
250	2	2	2	2	2	2	2	2	2	2
260	2	2	2	2	2	2	2	2	2	2
270	2	2	2	2	2	2	2	2	2	2
280	2	2	2	2	2	2	2	2	2	2
290	1	1	1	1	1	1	1	1	1	1
300	1	1	1	1	1	1	1	1	1	1
310	1	1	1	1	1	1	1	1	1	1
320	1	1	1	1	1	1	1	1	1	1
330	1	1	1	1	1	1	1	1	1	1
340	1	1	1	1	1	1	1	1	1	1
350	1	1	1	1	1	1	1	1	1	1
360	1	1	1	1	1	1	1	1	1	1

TABLE B I (d)

SOIL MOISTURE RETENTION TABLE – 100 mm

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 100 MM.

PE	0	1	2	3	4	5	6	7	8	9
					Water Retained in Soil					
0	100	99	98	97	96	95	94	93	92	91
10	90	89	88	88	87	86	85	84	83	82
20	81	81	80	79	78	77	77	76	75	74
30	74	73	72	71	70	70	69	68	68	67
40	66	66	65	64	64	63	62	62	61	60
50	60	59	59	58	58	57	56	56	55	54
60	54	53	53	52	52	51	51	50	50	49
70	49	48	48	47	47	46	46	45	45	44
80	44	44	43	43	42	42	41	41	40	40
90	40	39	39	38	38	38	37	37	36	36
100	36	35	35	35	34	34	34	33	33	33
110	32	32	32	31	31	31	30	30	30	30
120	29	29	29	28	28	28	27	27	27	27
130	26	26	26	26	25	25	25	24	24	24
140	24	24	23	23	23	23	22	22	22	22
150	22	21	21	21	21	20	20	20	20	20
160	19	19	19	19	19	18	18	18	18	18
170	18	17	17	17	17	17	16	16	16	16
180	16	16	15	15	15	15	15	15	14	14
190	14	14	14	14	14	14	13	13	13	13
200	13	13	12	12	12	12	12	12	12	12
210	12	11	11	11	11	11	11	11	11	11
220	10	10	10	10	10	10	10	10	10	10
230	9	9	9	9	9	9	9	9	9	9
240	8	8	8	8	8	8	8	8	8	8
250	8	8	8	7	7	7	7	7	7	7
260	7	7	7	7	7	7	6	6	6	6
270	6	6	6	6	6	6	6	6	6	6
280	6	6	6	6	6	6	5	5	5	5
290	5	5	5	5	5	5	5	5	5	5
300	5	5	4	4	4	4	4	4	4	4
310	4	4	4	4	4	4	4	4	4	4
320	4	4	4	4	4	4	4	4	4	4
330	3	3	3	3	3	3	3	3	3	3
340	3	3	3	3	3	3	3	3	3	3
350	3	3	3	3	3	3	3	3	3	2
360	2	2	2	2	2	2	2	2	2	2
370	2	2	2	2	2	2	2	2	2	2
380	2	2	2	2	2	2	2	2	2	2
390	2	2	2	2	2	2	2	2	2	2
400	2	2	2	2	2	2	2	2	2	2
410	2	2	2	2	2	1	1	1	1	1
420	1	1	1	1	1	1	1	1	1	1
430	1	1	1	1	1	1	1	1	1	1
440	1	1	1	1	1	1	1	1	1	1
450	1	1	1	1	1	1	1	1	1	1
460	1	1	1	1	1	1	1	1	1	1
470	1	1	1	1	1	1	1	1	1	1
480	1	1	1	1	1	1	1	1	1	1
490	1	1	1	1	1	1	1	1	1	1
500	1	1	1	1	1	1	1	1	1	1

TABLE B1 (e)

SOIL MOISTURE RETENTION TABLE – 125 MM

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 125 MM.

PE	0	1	2	3	4	5	6	7	8	9
				WATER RETAINED IN SOIL						
0	125	124	123	122	121	120	119	118	117	116
10	115	114	113	112	111	110	109	108	107	106
20	105	105	104	103	102	102	101	100	99	99
30	98	97	96	95	94	94	93	92	91	90
40	90	89	88	87	86	86	85	84	84	83
50	83	82	82	81	80	80	79	79	78	77
60	76	76	75	74	74	73	73	72	72	71
70	70	70	69	69	68	68	67	67	66	65
80	65	64	64	63	63	62	62	61	61	60
90	60	59	59	58	58	57	57	56	56	55
100	55	55	54	54	53	53	53	52	52	51
110	51	51	50	50	49	49	49	48	48	47
120	47	47	46	46	45	45	45	44	44	43
130	43	43	42	42	41	41	41	41	40	40
140	40	40	39	39	39	38	38	38	38	37
150	37	37	36	36	36	35	35	35	35	34
160	34	34	33	33	33	32	32	32	32	31
170	31	31	31	30	30	30	30	30	30	29
180	29	29	29	29	28	28	28	27	27	27
190	26	26	26	26	26	25	25	25	25	25
200	24	24	24	24	24	23	23	23	23	23
210	22	22	22	22	22	22	22	21	21	21
220	21	21	21	21	20	20	20	20	20	20
230	19	19	19	19	19	18	18	18	18	18
240	18	18	17	17	17	17	17	17	17	17
250	16	16	16	16	16	16	16	16	15	15
260	15	15	15	15	15	14	14	14	14	14
270	14	14	14	14	14	13	13	13	13	13
280	13	13	13	13	13	12	12	12	12	12
290	12	12	12	12	12	11	11	11	11	11
300	11	11	11	11	11	10	10	10	10	10
310	10	10	10	10	10	10	10	10	9	9
320	9	9	9	9	9	9	9	9	9	9
330	8	8	8	8	8	8	8	8	8	8
340	8	8	8	8	8	7	7	7	7	7

* * * * * * * * * * * * * * * * * * *

PE	0	5	PE	0	5	PE	0
350	7	7	450	3	3	550	1
360	7	6	460	3	3	560	1
370	6	6	470	3	3	570	1
380	5	5	480	2	2	580	1
390	5	5	490	2	2	590	1
400	5	5	500	2	2	600	1
410	4	4	510	2	2	610	1
420	4	4	520	2	2	620	1
430	4	4	530	2	2	630	1
440	3	3	540	2	1	640	1

TABLE B I (a)

SOIL MOISTURE RETENTION TABLE – 125 MM

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 125 MM.

PE	0	1	2	3	4	5	6	7	8	9
				Water Retained in Soil						
0	125	124	123	122	121	120	119	119	117	116
10	115	114	113	112	111	110	109	108	107	106
20	106	105	104	103	102	102	101	100	99	99
30	98	97	96	95	94	94	93	92	91	90
40	90	89	88	87	86	86	85	84	84	63
50	83	82	82	81	80	80	79	79	78	77
60	76	76	75	74	74	73	73	72	72	71
70	70	70	69	69	68	68	67	67	66	65
80	65	64	64	63	63	62	62	61	61	60
90	60	59	59	58	58	57	57	56	56	55
100	55	55	54	54	53	53	53	52	52	51
110	51	51	50	50	49	49	49	48	48	47
120	47	47	46	46	45	45	45	44	44	43
130	43	43	42	42	41	41	41	41	40	40
140	40	40	39	39	39	38	38	38	38	37
150	37	37	36	36	36	35	35	35	35	34
160	34	34	33	33	33	32	32	32	32	31
170	31	31	31	30	30	30	30	30	30	29
180	29	29	29	29	28	28	28	27	27	27
190	25	26	26	26	26	25	25	25	25	25
200	24	24	24	24	24	23	23	23	23	23
210	22	22	22	22	22	22	22	21	21	21
220	21	21	21	21	20	20	20	20	20	20
230	19	19	18	19	19	18	18	18	18	18
240	18	18	17	17	17	17	17	17	17	17
250	16	16	16	16	16	16	16	16	15	15
260	15	15	15	15	15	14	14	14	14	14
270	14	14	14	14	14	13	13	13	13	13
280	13	13	13	13	13	12	12	12	12	12
290	12	12	12	12	12	11	11	11	11	11
300	11	11	11	11	11	10	10	10	10	10
310	10	10	10	10	10	10	10	10	9	9
320	9	9	9	9	9	9	9	9	9	9
330	8	8	8	8	8	8	8	8	8	8
340	8	8	8	8	8	7	7	7	7	7

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	0	5		0	5		0
350	7	7	450	3	3	550	1
360	7	6	460	3	3	560	1
370	6	6	470	3	3	570	1
380	6	5	480	2	2	580	1
390	5	5	490	2	2	590	1
400	5	5	500	2	2	600	1
410	4	4	510	2	2	610	1
420	4	4	520	2	2	620	1
430	4	4	530	2	2	630	1
440	3	3	540	2	1	640	1

TABLE B I (f)

SOIL MOISTURE RETENTION TABLE - 150 mm

SOIL MOISTURE RETAINED AFTER DIFFERENT AMOUNTS OF POTENTIAL EVAPOTRANSPIRATION HAVE OCCURRED. WATER HOLDING CAPACITY OF SOIL IS 150 MM.

PE	0	1	2	3	4	5	6	7	8	9
					Water Retained in Soil					
0	150	149	148	147	146	145	144	143	142	141
10	140	139	138	137	136	135	134	133	132	131
20	131	130	129	128	127	127	126	125	124	123
30	122	122	121	120	119	118	117	116	115	114
40	114	113	113	112	111	111	110	109	108	107
50	107	106	106	105	104	103	103	102	101	100
60	100	99	98	97	97	97	96	95	94	93
70	93	92	92	91	90	90	89	89	88	87
80	87	86	86	85	84	84	84	83	83	82
90	82	81	81	80	79	79	78	77	77	76
100	76	76	75	75	74	74	73	72	72	71
110	71	71	70	70	69	69	68	68	67	67
120	66	66	66	65	65	64	64	63	63	62
130	62	62	61	61	60	60	60	59	59	58
140	58	58	57	57	56	56	55	55	54	54
150	54	53	53	53	52	52	52	52	51	51
160	51	51	50	50	50	49	49	48	48	47
170	47	47	47	46	46	46	45	45	45	44
180	44	44	44	43	43	43	42	42	42	41
190	41	41	41	40	40	40	40	39	39	39
200	39	38	38	38	37	37	37	37	36	36
210	36	36	35	35	35	35	35	34	34	34
220	34	34	33	33	33	33	33	32	32	32
230	32	31	31	31	31	31	30	30	30	30
240	30	29	29	29	29	29	28	28	28	28
250	28	27	27	27	27	27	26	26	26	26
260	26	26	25	25	25	25	25	24	24	24
270	24	24	24	23	23	23	23	23	23	23
280	22	22	22	22	22	22	22	22	21	21
290	21	21	21	20	20	20	20	20	20	20
300	20	19	19	19	19	19	19	19	18	18
310	18	18	18	18	18	18	18	17	17	17
320	17	17	17	17	17	17	17	16	16	16
330	16	16	16	16	16	16	16	15	15	15
340	15	15	15	15	15	15	14	14	14	14
350	14	14	14	14	14	14	14	13	13	13
360	13	13	13	13	13	13	13	12	12	12
370	12	12	12	12	12	12	12	12	11	11
380	11	11	11	11	11	11	11	11	11	11
390	11	11	11	10	10	10	10	10	10	10
400	10	10	10	10	10	10	10	10	9	9
410	9	9	9	9	9	9	9	9	9	9
420	9	9	9	8	8	8	8	8	8	8
430	8	8	8	8	8	8	8	8	8	8
440	8	8	8	7	7	7	7	7	7	7

SOIL MOISTURE RETENTION TABLE – 150 MM

(CONTINUED)

PE	0	1	2	3	4	5	6	7	8	9
					WATER RETAINED IN SOIL					
450	7	7	7	7	[illegible]	7	7	7	7	7
460	7	7	7	7	[illegible]	6	6	6	6	6
470	6	6	6	6	[illegible]	6	6	6	6	6
480	6	6	6	6	[illegible]	6	6	6	6	6
490	5	5	5	5	[illegible]	5	5	5	5	5
500	5	5	5	5	[illegible]	5	5	5	5	5
510	5	5	5	5	[illegible]	5	5	5	4	4
520	4	4	4	4	[illegible]	4	4	4	4	4
530	4	4	4	4	[illegible]	4	4	4	4	4
540	4	4	4	4	[illegible]	4	4	4	4	4
550	4	4	4	4	[illegible]	4	4	3	3	3
560	3	3	3	3	[illegible]	3	3	3	3	3
570	3	3	3	3	[illegible]	3	3	3	3	3
580	3	3	3	3	[illegible]	3	3	3	3	3
590	3	3	3	3	[illegible]	3	3	3	3	3
600	3	3	3	3	[illegible]	2	2	2	2	2
610	2	2	2	2	[illegible]	2	2	2	2	2
620	2	2	2	2	[illegible]	2	2	2	2	2
630	2	2	2	2	[illegible]	2	2	2	2	2
640	2	2	2	2	[illegible]	2	2	2	2	2
650	2	2	2	2	[illegible]	2	2	2	2	2
660	2	2	2	2	[illegible]	2	2	2	2	2
670	2	2	2	2	[illegible]	2	2	2	2	2
680	2	2	1	1	[illegible]	1	1	1	1	1
690	1	1	1	1	[illegible]	1	1	1	1	1
700	1	1	1	1	1	1	1	1	1	1
710	1	1	1	1	1	1	1	1	1	1
720	1	1	1	1	1	1	1	1	1	1
730	1	1	1	1	1	1	1	1	1	1
740	1	1	1	1	1	1	1	1	1	1

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PE	0	5	PE	0	5	PE	0	5
750	1	1	790	1	1	830	1	1
760	1	1	800	1	1	840	1	1
770	1	1	810	1	1			
780	1	1	820	1	1			

APPENDIX C : PERCOLATION MEASUREMENT BY WATER BALANCE.

The daily meteorological data at Linbro Park between 1 September 1987 and 31 August 1988 was used to estimate percolation into the fill over that period. A number of basic assumptions and measurements were made as follows :

a) The soil is a decomposed granite with 79,5% sand fraction and 20,5% silt and clay fraction but has low permeability and thus a below average infiltration capacity. Therefore use hydrologic soil group B/C (Appendix A).

b) Use antecedent soil moisture condition 1 : if no rain for 10 days or more

2 : if no rain for more than 1 day.

3 : if more than 10mm fell on previous day or more than 25mm fell in previous 3 days. (At a permeability of 1×10^{-5}cm/s water will seep 8,6 mm/day for I = 1)

c) Consider land use as range land (poor condition) or pervious areas (poor grass). Therefore CN = 83.

d) Available water storage is 100mm (Thornthwaite and Mather (73)).

e) Depth of top cover = 1 m.

f) Potential evapotranspiration = 0,7 x pan evaporation.

From the *calculations* it appears that percolation first occurs on 30 November 1987, on 3 days in December 1987 and then again for 5 days in March 1988 for a total of 64,4 mm in the year. Doing the same calculation but using a runoff factor of 0,1125, *percolation* also first appears in *November 1987*, but results in a total of 133mm for the year.

Doing the same calculation on a monthly basis, there will be zero percolation in the *year using* the SCS method for runoff calculation, but there will be 4mm using a runoff factor of 0,1125.

APPENDIX D : FIELD CAPACITY DETERMINATION FOR REFUSE.

Field capacity of refuse was determined using two different methods :

1. Refuse was placed into 170 litre polyethylene bins and compacted by hand to different densities. The initial moisture content of the refuse was taken from a representative sample. The refuse was then soaked in a measured volume of water (using a flow meter) for 24 hours. Holes were then drilled into the base of the bins and the water allowed to drain into a measuring container overnight (this was done to reduce the effect of evaporation). This method was only used for fresh refuse and was a more crude method than method 2. Results can be seen in Table D1.

2. A steel cylinder of diameter 395mm and height 535mm was used to hold the refuse. Holes were drilled into the side of the cylinder, level with its base, to drain the water. The inside was lined with a geofabric before placing the refuse in its loose state. The refuse was soaked in water for 5 hours and then allowed to drain overnight.

The refuse was then compressed in an Amsler loading machine to different densities while measuring the volume of water seeping out. The procedure was done for 3 different ages of refuse, (fresh, 1 year old and 5 year old), and results can be seen in Tables D2 and Figure 3.12.

Table D 1

Refuse mass	Refuse Volume (m^3)	Initial w (%)	Dry Density (kg/m^3)	Water Retained (l)	Wet density (kg/m^3)	Field capacity (%)
32,7	0,17	25,0	153,0	97,4	726	375
59,5	0,17	27,8	163,5	101,1	868	217
48,9	0,17	22,4	235,3	100,4	825	251
62,3	0,17	35,3	290,0	79,7	759	162
33,7	0,152	35,4	163,5	35,7	398	143,4
47,0	0,16	30,2	225,6	45,5	510	125,0
86,2	0,16	31,6	409,4	57,2	757	87,3
60,0	0,16	35,2	275,6	45,8	562	103,9

TABLE D2 σ=stress

δ=deflection

h=refuse height

ε=[illegible]

w=water content (% of dry mass)

ρ=density (w=wet; d=dry)

LOAD (kN)	σ (kPa)	δ (mm)	(mm)	ε	WATER (l)	w (%)	ρ_w (kg/m^3)	ρ_d (Kg/m^3)
Test 1: m_i=8,2kg, h_i=435mm, w_i=15,8% fresh refuse.								
0	0	0	435	0	7,30	119	306	140
0,91	7,8	150	285	0,34	6,94	114	456	213
9,91	83,1	247	188	0,57	5,71	96	636	324
16,91	145,3	279	156	0,64	5,35	91	746	390
24,91	214,0	300	135	0,69	5,11	88	847	451
32 91	282,7	320	115	0,74	4,75	83	967	529
40,91	351,5	330	105	0,76	[illegible]	79	1039	579
Test 2: m_i=6,6kg, h_i=385mm, w_i=53,4% fresh refuse.								
0	0	0	385	0	7,60	230	317	96
0,99	8,5	165	220	0,43	7,11	219	535	168
8,99	77,2	264	121	0,69	4,64	161	798	305
16,99	146,0	288	97	0,75	3,90	144	930	381
24,99	214,7	301	84	0,78	3,38	132	1021	440
32,99	283,4	315	70	0,82	2,90	121	[illegible]	528
40,99	352,1	322	63	0,84	2,35	108	1220	586

(Table D2 Continued)

LOAD (kN)	σ (kPa)	δ (mm)	h (mm)	ε	WATER (l)	w (%)	ρ_w (kg/m³)	ρ_d (kg/m³)
Test 3: m_i=18,1kg,		h_i=405mm,		w_i=40,4%,		[illegible] year old refuse.		
0	0	0	405	0	4,90	78,3	488	274
0,73	6,3	103	302	0,25	4,72	76,9	649	367
8,73	75,0	185	220	0,46	4,04	71,6	865	504
16,[illegible]	143,7	220	185	0,54	3,26	65,5	992	599
24,73	212,[illegible]	241	164	0,60	2,49	59,6	1078	676
32,73	281,2	255	150	0,63	2,02	55,9	1152	739
40,73	349,9	261	144	0,64	1,62	52,1	1170	769
Test 4: m_i=2[illegible],7kg,		h_i=435mm,		w_i=46,2%,		1 year old refuse.		
0	0	0	435	0	4,08	74,5	489	280
0,73	6,3	94	341	0,22	3,96	73,7	621	356
8,73	75,0	222	213	0,51	3,33	69,2	969	573
16,73	143,7	248	187	0,57	2,73	65,0	1076	652
24,73	212,5	261	174	0,60	[illegible],28	61,8	1135	701
32,73	281,2	275	160	0,63	1,66	57,6	1202	762
40,73	349,9	281	154	0,65	1,20	54,2	1222	792

(TABLE D2 Continued)

LOAD (kN)	σ (kPa)	δ (mm)	h (mm)	ε	WATER (l)	* (%)	ρ_w (kg/m^3)	ρ_d (kg/m^3)
Test 5: m_i=15,0kg,		h_i=380mm,		w_i=42,3%,		5 year old refuse.		
0	0	0	380	0	4,85	89,0	449	237
0,73	6,3	85	295	0,22	4,62	86,9	571	306
8,73	75,0	198	182	0,52	4,24	83,2	908	496
16,73	143,7	221	159	0,58	3,72	78,3	1011	567
24,73	212,5	235	145	0,62	3,49	76,1	1096	622
32,73	281,2	245	135	0,64	3,12	72,5	1153	668
40,73	349,9	250	130	0,66	2,70	68,5	1169	694
Test 6: m_i=14,2kg,		h_i=455mm,		w_i=35,4%,		5 year old refuse.		
0	0	0	455	0	4,40	77,1	351	198
0,73	6,3	127	328	0,28	4,40	77,1	487	275
8,73	75,0	268	187	0,59	3,98	73,1	835	483
16,73	143,7	295	160	0,65	3,58	69,3	955	564
24,73	212,5	308	147	0,68	3,33	66,9	1024	614
32,73	281,2	318	137	0,70	2,95	63,3	1075	659
40 73	349,9	325	130	0,71	2,49	59,0	1103	694

APPENDIX E ; PERMEABILITY DETERMINATION *OF REFUSE.*

The permeability determination was an extension of the field capacity test in Appendix D. A shower nozzle was used at the end of a flow meter so that the rate of *"showering" the refuse equalled the rate of* water seeping out of the base. Times were then taken for volumes of water to seep through the waste and the permeability equated by :

$$K' = QL/thA$$

where Q = volume of flow (cm^3)

i = h/L = 1 in this case

t = *time* in seconds

A = cross sectional area (cm^2)

Due to the inconsistency of refuse *itself properties such* as *permeability or field* capacity are impossible to pin-point accurately, but a "ballpark" figure can be used with relative confidence. Results are shown in Table E 1 and in Figure 3.13.

Table E 1

Refuse Dry density (kg/m^3)	Refuse Wet density (kg/m^3)	Volume of Flow (cm^3)	Time (Seconds)	Area (cm^2)	Permea-bility k (cm/sec)
153,0	726	90000	17860	2050	$2,5\times10^{-3}$
163,5	868	90000	14760	2050	$3,0\times10^{-3}$
235,3	825	90000	2700	2050	$1,6\times10^{-2}$
290,0	759	90000	13320	2050	$3,3\times10^{-3}$
163,8	398	90000	18960	2050	$2,3\times10^{-3}$
225,6	510	90000	12780	2050	$3,4\times10^{-3}$
409,4	767	80000	12300	2050	$3,2\times10^{-3}$
276,6	562	90000	11820	2050	$3,7\times10^{-3}$

APPENDIX F : DETERMINATION OF REFUSE MOISTURE CONTENT.

Previously the moisture content of refuse was determined by oven drying a sample at 105°C for 24 hours (Ball [57]) and van Rensburg [76]). However observations of the *refuse show* that *some* putrescibles begin decomposing very quickly at this temperature, and certain volatile organics are driven off. A test was run on a number of samples drying at 50°C and was found to *stabilise after between* 5 and 6 days the temperature was then increased to 105°C for 24 hours and the extra "moisture" given off was calculated.

The moisture content in all cases is that determined after oven drying at 50°C for 7 days on a percentage of dry weight basis.

APPENDIX G : EXTRACTION OF LIQUOR FOR ANALYSIS.

The extraction process was developed so that, even if a quantitative calculation of pollution is not possible, it can be a standard for a comparative evaluation of the refuse.

The extraction involved the addition of 500ml of distilled water at 18°C to 2000g of refuse. The mixture was then vibrated at a frequency of 50 Hz for 30 minutes. The supernatent liquor was then drained through a rough filter (in this case a "Bidim U14" geofabric) into a clean 1 litre bottle. A further 500ml of distilled water was added and the process repeated. It was repeated again for a third time. The liquor thus extracted was then centrifuged at 9000 rpm for between 10 and 15 minutes to remove all the suspended solids. It was then stored in the refrigerator at 4°C until it was sent to the laboratory for analysis.

The results from the laboratory were given in mg/l of the liquid sent for analysis. To ensure that comparisons were consistent the units were then converted to mg/kg of dry refuse by the formula:

$$mg/dry\ kg = mg/litre \times (1,5\ litre\ (1 + w)/2kg)$$

where : w = moisture content of the refuse (on a dry weight basis).

APPENDIX H: WATER BALANCE CALCULATIONS FOR LINBRO AND COASTAL PARKS.

The water balance has been calculated at *Linbro Park and* at *Coastal Park* using 20 year mean rainfall and evaporation figures as supplied by the South African Weather Bureau (see section 3.3.1). The calculations are shown in tables H1(a) and (b) below and results are plottedin figure3.9.

TABLE H1 (a) COASTAL PARK WATER BALANCE

MONTH	PET	RAIN	R/OFF			ST	ΔST	AET	PERC
JAN	142	32	2	-112	[illegible]	4	-5	35	0
FEB	110	31	2	-81	-405	2	-2	31	0
MAR	84	48	4	-40	-445	1	-1	45	0
APR	57	54	4	-7	-452	1	0	50	0
MAY	32	108	8	+68		69	+68	32	0
JUN	30	124	9	+85		100	+31	30	54
JUL	29	127	10	+88		100	0	29	88
AUG	36	96	7	+53		100	0	36	53
SEP	52	70	5	+13	(0)	100	0	52	13
OCT	90	57	4	-37	-37	68	-32	84	0
NOV	118	33	2	-87	-124	28	-40	71	0
DEC	124	39	3	-88	-212	11	-17	53	0

TABLE H1 (b) LINBRO PARK WATER BALANCE

MONTH	PET	RAIN	R/OFF	I	PE	ST	ΔST	AET	PERC
JAN	132	214	24	+58		88	+58	132	0
FEB	110	138	16	+12		100	+12	110	0
MAR	101	153	17	+35	(0)	100	0	101	35
APR	80	78	9	-11	-11	89	-11	80	0
MAY	76	34	4	-46	-59	54	-35	65	0
JUN	60	15	2	-47	-106	34	-20	33	0
JUL	64	10	1	-55	-161	19	-15	24	0
AUG	85	19	2	-68	-229	10	-9	26	0
SEP	101	61	7	-47	-276	6	-4	58	0
OCT	111	121	14	-4	-280	6	0	107	0
NOV	126	166	19	+21		27	+21	126	0
DEC	127	146	16	+3		30	+3	127	0

PET = potential evapotranspiration = 0,7 x pan evaporation

I = rain - runoff - PET

PE = $\Sigma I_{negative}$

ST = soil moisture storage

AET = actual evapotranspiration

PERC = percolation (or production of leachate)

APPENDIX I: PREDICTED PERCOLATION AT LINBRO PARK

Section 3.3.1 produces a percolation figure at Linbro Park of *136mm p.a.* below a 1000mm vegetated cover, and 213mm p.a. below a 200mm bare soil cover. The moisture holding capacity of the soil is its *field capacity (15%) minus* the wilting point (3%), and its in situ dry density is 1620 kg/m^3.

Therefore the volumetric water holding capacity = 194mm/m

Similarly the refuse field capacity (60%) less initial moisture content (20%) and in situ dry density of 824 kg/m^3 gives a water holding capacity for municipal refuse = 330mm/m.

For predicting percolation the profile is considered in two stages, that tipped before 1976 and that tipped in 1986. Assume 6 years subject to 200mm cover, then 9 years under 1m cover, then 2 years under 200mm, and finally 1,5 years under 1m of vegetated cover. The total percolation is then :

6 x 213 + 9 x 136 + 2 x 213 + 1,5 x 136 = 3240mm

Extra moisture holding capacity for each hole is :

a) *North hole* - *5900mm* soil = 1145mm moisture

8750mm refuse = 2889mm moisture

2800mm *mixed* = *848mm moisture*

Total moisture = 4882mm

b) South hole - 9850mm soil = 1911mm moisture

6250mm refuse = 2063mm moisture

3900mm mixed = 1182mm moisture

Total moisture = *5156mm*

APPENDIX J: MEASUREMENT OF EXTRA MOISTURE AT LINBRO PARK

To measure the total moisture in each hole the water content as *measured in* the laboratory was applied to each layer (soil or refuse) to get a volumetric measure of total water using known dry densities.

This resulted in a total water content of 4715mm in the north hole and 5420mm in the south hole at the end of the wet season, and 3846mm (north hole) and 3603mm (south hole) at the end of the dry season.

Initial moisture conditions in the profile had to then be subtracted to calclate the additional moisturein the holes. Based on refuse initial moisture of 20% and soil of 3% gives initial conditions as 2112mm moisture in the north hole and 1836mm in the south hole. *Table J1 summarises the results below:*

TABLE J1 ADDITIONAL MOISTURE IN PROFILE

	End wet season	End dry season
NORTH HOLE	2603mm	1734mm (33% reduction)
SOUTH HOLE	3584mm	1757mm (50% reduction

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