# A REVIEW OF

# APPROACHES AND METHODOLOGIES FOR DETERMINING LEACHATE GENERATION AT WASTE DISPOSAL SITES AND GROUNDWATER RECHARGE

report prepared for

**Water Research Commission**

by


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***EXECUTIVE SUMMARY***

# *A Review of Approaches and Methodologies for Determining Leachate Generation at Waste Disposal Sites and Groundwater Recharge*

*Roger Parsons*

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## *Problem Statement*

*From a geohydrological point of view, it is relatively simple to show that groundwater recharge occurs throughout the country, irrespective of climatic conditions. The quantification of recharge is, however, difficult. The classical Waste Site Water Balance method, on the other hand, has and is being widely applied in South Africa to determine or predict leachate generation at waste disposal sites. "Regarding precipitation, it has become generally accepted that in areas where the annual evapotranspiration rate exceeds the annual precipitation rate, ie. water deficit climates, water contamination due to landfill leachate is not a problem." (Ball, 1984, p. 16). This suggests that leachate only poses a threat to groundwater in 20 % of South Africa. Both approaches are primarily based on climatic considerations, yet yield apparently contradictory results. This apparent paradox between the Waste Site Water Balance and groundwater recharge approaches, coupled with the widespread acceptance and application of the classical Waste Site Water Balance method to predict leachate generation and the proposal to use a Climatic Water Balance to define minimum requirements at waste disposal sites prompted the proposal to the Water Research Commission.*

## *Research Objectives*

*The objectives of the research project were to evaluate approaches employed locally and internationally to determine **recharge** and **leachate generation** in order to identify the more appropriate approach. The specific objectives of the research project were, therefore, as follows:*

- *to assess approaches and methodologies employed internationally to determine rates of recharge and leachate generation at waste disposal sites.*

- *to assess approaches and methodologies employed in South Africa to determine rates of recharge and leachate generation at waste disposal sites.*
- *to compare the approaches and methods identified in (a) and (b) in order to evaluate the current knowledge and practices in South Africa.*
- *to identify further research needs in this field in South Africa.*

***Research Method***

*The research was carried out by means of a detailed literature study and discussions with selected proponents of the two approaches. Further a short course entitled "An introduction to microbiology of landfills and landfill gas" was attended. Mr Andrew Stone of the American Ground Water Trust was appointed to investigate current practice and approaches used in the USA with regard to waste management, leachate generation and groundwater contamination. The project was carried out over a 9 month period and this report represents the completion of the literature-based project.*

***Leachate Generation***

*Leachate is generated as a result of the percolation of water or other liquids through any waste and by the compaction of the waste due to its weight. The classical Waste Site Water Balance method aims to predict the volume of leachate that will be produced by a waste site. Water input (precipitation and moisture of waste) is balanced against water losses (run-off, evapotranspiration, vapour losses in gas) plus the change in storage. Even though the method has not been fully validated, it is widely used to predict leachate generation, determine co-disposal (solid / liquid) ratios, define waste site design and management requirements and for waste site classification purposes. The following is a list of some of the more important aspects which require attention when considering leachate generation and the estimation thereof:*

- *It was found that the quantification of the factors considered in the water balance is difficult.*
- *The volume of precipitation is probably the easiest to measure, but the nature and intensity of precipitation is not considered.*
- *Run-off and infiltration are usually estimated using either the rational method or the SCS curve number method.*
- *The initial moisture content of the waste and moisture resulting from waste decomposition are, respectively, difficult to measure accurately and the focus of much debate. The latter is usually regarded as small and hence ignored.*
- *Lateral subsurface inflow only has to be considered if the waste pile is located beneath the water table.*
- *Evapotranspiration is the most difficult to quantify of all the parameters considered by the Waste Site Water Balance method. It is also the most crucial. A number of methods are available to estimate evapotranspiration but all suffer from some limitations. The most significant limitation is that evapotranspiration is limited in arid areas by the availability of water and not energy. Antecedent soil moisture conditions thus also need to be considered.*
- *The estimation of the volume of water stored in the waste is also difficult. Here heterogeneity*

*and unsaturated conditions play a role.*

- *Intrinsically, the Waste Site Water Balance method ascribes to the principle that leachate will not be generated until the soil moisture deficit has been satisfied. This principle has in fact been found to be invalid by a number of workers. Flow through preferential flow channels can lead to leachate being generated at a far earlier stage.*

*A number of computer models have been developed to determine leachate generation. The best known of these is HELP (Hydrological Evaluation of Landfill Performance). Even though such models have the advantage in that large data sets can be managed and tedious repetitive work is avoided, the models still suffer from the same limitations and inaccuracies as the classical approach. Further, the validation of these models using real site data has been found wanting.*

*Three facets which could impact on the accuracy of the method, and which are not addressed in the classical approach, were identified. These are:*

- *the positive impacts of site design and management*
- *the dynamics of arid zone hydrology, and*
- *changes over time.*

***Groundwater Recharge***

*Recharge is the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. Even though it is an important consideration in geohydrological studies, it is difficult to quantify with any certainty. Recharge is controlled by similar processes and factors as leachate generation. Numerous techniques are available for the estimation of recharge, most of which are based on independent approaches. The quantification of recharge in arid climates is at present receiving worldwide attention. Some important considerations include:*

- *Precipitation and the nature of the precipitation are of paramount importance to recharge in arid and semi-arid regions. Rainfall is generally episodic and hence prone to the fallacy of averaging.*
- *Even though evapotranspiration is recognised as playing a role in recharge, this near-surface process need not be considered in the estimation of recharge.*
- *Unlike the case of leachate generation estimation, lateral water movement has to be considered. With sufficient data and the application of Darcy's Law, reasonable estimates can be made.*
- *The accurate estimation of storativity is critical to some of the estimation approaches. This is problematic, particularly when dealing with fractured aquifer systems.*

*No single, comprehensive estimation technique has yet been identified which can model recharge without yielding suspect results. The availability of a number of different, independent techniques does however furnish the opportunity to compare results. Some of the important findings include:*

- *Groundwater Balance Methods were found to yield reasonable results but are best suited for first approximations.*

- *Soil Moisture Budgeting methods, which are based on the same underlying principles as the classical Waste Site Water Balance method, were found to be invalid under arid climates. Further, their reliance on evapotranspiration, the averaging of data, their lack of consideration of preferred pathways and the assumption that soil moisture deficit has to be satisfied before recharge could occur were also identified as drawbacks.*
- *Empirical approaches are popular as first approximations, and by continual re-evaluation, are being found to be reliable. Here a percentage of mean annual precipitation is considered to effectively recharge groundwater bodies.*
- *Spring flow has also been used successfully as the basis for recharge quantification.*
- *The comparison of chemical or isotopic constituents in rainwater and groundwater have formed the basis of tracer approaches to recharge estimation. Even though these approaches have some disadvantages, valuable information has been obtained from their application.*

*Numeric modelling, as with leachate estimations, has become popular in the determination of recharge. Models, however, still suffer from the same shortcomings as the approach upon which they are based. Other approaches were identified in the literature, but the above discussed techniques were regarded as the best recognised and most widely applied.*

*A number of case studies, dealing particularly with recharge in arid areas, were researched. It was clearly established the aquifers are recharged, even under very dry conditions. It was found that recharge occurs infrequently, that preferential flow was an important mechanism in the process and that recharge usually only occurs after major rain events.*

***Comparison of the Two Approaches***

*Approaches and techniques used in the estimation of leachate generation and recharge were compared. It was found that even though the two approaches share some similarities, a number of significant differences in process and method of calculation exist:*

- *A major difference between the Waste Site Water Balance method and recharge estimation techniques lies in the validation of the predicted outcome. As recharge ultimately defines the volume of water that can be abstracted from an aquifer over the long-term, it is sound management practice to continually check and update estimates of recharge using all available data. This can be done through observing aquifer response to pumpage, applying a number of different techniques and retrospective checking. As a result of this continual re-assessment, recharge estimations have been validated and reasonable estimates can be made. Leachate generation, on the other hand, can only be observed indirectly and observation is not assured. Further, leachate generation methods are all based on the balancing or budgeting approach and thus do not have the benefit of independent comparison. Leachate generation estimations were also found to be rarely checked, especially using real site data. The validation of the technique thus remains in question.*

- *It was found that the calculation of output as a residual was a problem. The use of the residual approach results in the errors of all the fluxes accumulating in the answer. It was also shown* *that a small change in one of the components of the balance resulted in a significant change in the answer. The use of the water balance approach in both leachate generation estimation and recharge estimation was concluded to be inappropriate.*

- *The question of scale was also found to be a key difference. Recharge is considered on a regional scale while leachate generation is assessed on a localised scale. The large scale allows for generalizations to be made as the physical environment tends toward homogeneity. The smaller scale requires that more detail be considered and generalizations are less applicable. Processes have to be considered in more detail than in the case of large scale investigations. The need for more detail makes leachate generation more difficult and more prone to error.*

- *In a similar vein, depth also has to be considered. Waste disposal, and hence leachate generation, occurs at surface while groundwater recharge occurs below surface. This has the implication that evapotranspiration has to be considered in leachate generation and not in recharge estimation and that recharge is the end product of the infiltration and percolation process. Both of these issues point to leachate generation being more complex to determine than groundwater recharge.*

- *The most significant difference between the two approaches, however, is that classical water budgeting techniques are not valid under arid and semi-arid climatic conditions. This includes balancing and budgeting approaches used to estimate leachate generation and the soil moisture budgeting techniques used to determine groundwater recharge. It is argued in the literature that budgeting techniques were developed in wetter, humid climates and then applied to arid climates. The moisture movement mechanisms are different under the two types of climate and the dynamic of arid zone hydrology is not considered.*

***Concluding Comments***

*The fundamental differences between leachate generation and groundwater recharge suggest that the two processes do not equate. Leachate generation occurs near surface as water passes through the landfill, exiting usually at or near the base of the system. Precipitation is also not the only source of water in the generation of leachate as additional moisture can be derived from the incoming waste as well as from chemical and biological activity within the waste pile. Groundwater recharge, on the other hand, is essentially an end product ie. the volume of water that can or does enter the aquifer system which results in replenishment. These differences indicate that a direct comparison between the two is not legitimate. Further, because of the different scales involved in trying to predict output, the estimation techniques are also not interchangeable. It thus cannot be stated that one approach is more appropriate than the other. It can also not be stated that recharge estimation techniques can be used to predict leachate generation. However, it can be stated that the comparison made between the two methods has highlighted flaws in the WSWB method.*

*A strong need exists for the transfer of knowledge between disciplines, especially from focused disciplines into multi-disciplinary arenas such as waste management. The estimation of recharge has benefited from that fact that recharge is easily observable and that estimation follows a retrospective approach. Further* *the continual checking of estimates has lead to the validation of the various techniques applied to recharge estimation. The knowledge relating particularly to the limitations of applying the water balance technique to arid climates needs to be highlighted.*

*The continual use of the classical Waste Site Water Balance method to predict leachate generation, determining co-disposal (solid / liquid) ratios and defining site design and management requirements needs to be addressed. Until such time that reliable leachate generation tools become available, a conservative approach to the problem needs to be taken. The waste management community needs to be made aware of the limitations in estimating leachate generation. This can be achieved through seminars, workshops, publication of articles and the wide distribution of this report.*

*Finally, it is recommended that a workshop be arranged to debate the problem of leachate generation estimation and to see whether it is possible to identify a practical tool capable of providing reasonable estimates. Such a workshop is regarded as an alternative to initiating difficult, time consuming, expensive research.*

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*A review of approaches and methodologies for determining recharge and leachate generation rates at waste disposal sites*

The Steering Committee responsible for this project consisted of the following persons:

| | |
|---|---|
| Mr AG Reynders | Water Research Commission (Chairman) |
| Mr HM du Plessis | Water Research Commission |
| Mr JM Ball | Jarrod Ball and Associates |
| Prof GE Blight | University of Witwatersrand |
| Mr L Bredenhann | Department of Water Affairs and Forestry |
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| Dr M Levin | Atomic Energy Corporation of South Africa |
| Mr G Strayton | Institute of Waste Management |
| Mr JMC Weaver | CSIR |
| Mrs AM du Toit | Water Research Commission (Secretary) |

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| | |
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| Dr S Kienzle | University of Natal |
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| Mr H Robinson | Aspinwall and Co. |
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Finally I would like to express my sincere appreciation to all persons in our country who contribute to the debate of waste management and who have as their ultimate goal responsible waste disposal. Through positive contributions our learning process can only improve, even if our deliberations seldom merge.

# TABLE OF CONTENTS



## CONTENTS

## LIST OF FIGURES



## LIST OF TABLES



## APPENDICES

## ABBREVIATIONS

*(unless otherwise explicitly stated, the following abbreviations are used)*

| | |
|---|---|
| A | area |
| a | annum |
| Abs | groundwater abstraction |
| B | water balance |
| b | threshold below which recharge does not take place |
| d | day |
| E | potential evaporation X 0.7 |
| $E_a$ | actual evaporation |
| $E_m$ | measured pan evaporation |
| $E_p$ | potential evaporation |
| ER | effective rainfall |
| Et | evapotranspiration |
| $Et_a$ | actual evapotranspiration |
| $Et_p$ | potential evapotranspiration |
| G | vapour loss in gas |
| ha | hectare |
| i | hydraulic gradient |
| I | infiltration |
| K | hydraulic conductivity |
| L | litres |
| m | meters |
| mm | millimetres |
| n | porosity |
| P | precipitation |
| Q | discharge |
| R | run-off |
| Re | recharge |
| $R_o$ | run-off |
| S | storage (or specific yield) |
| T | transmissivity |
| t | ton |
| w | cross-sectional width (m) |
| $W_m$ | moisture content of waste |
| $\Delta h$ | change in groundwater level |
| $\Delta S$ | change in storage |
| $\Delta t$ | change in time |

*(Standard chemical abbreviations are used throughout this text)*

# ACRONYMS

| | |
|---|---|
| ACRU | Agricultural Catchment Research Unit, University of Natal (SA) |
| CWB | Climatic Water Balance |
| DoE | Department of Environment (UK) |
| DWAF | Department of Water Affairs and Forestry (SA) |
| EPA | Environmental Protection Agency (US) |
| ESMD | Estimated Soil Moisture Deficit |
| GLF | Groundwater Level Fluctuation |
| HELP | Hydrological Evaluation of Landfill Performance |
| MAP | Mean Annual Precipitation (mm/a) |
| MORECS | Meterological Office Rainfall and Evaporation Calculation System |
| SCS | Soil Conservation Services (US Department of Agriculture) |
| SMD | Soil Moisture Deficit |
| SVF | Saturated Volume Fluctuation |
| WRC | Water Research Commission (SA) |
| WSWB | Waste Site Water Balance |

# 1. INTRODUCTION

## 1.1. Problem Statement

The fact that groundwater resources are important to national water supply strategies and that groundwater faces a threat from waste disposal activities is well documented (Parsons, 1992; Stone, 1991: Braune, 1990). Many scientific, technical and engineering problems exist in the field of waste disposal and the prevention of environmental contamination. Numerous theories have been proposed, particularly in America and Europe, pertaining to means of reducing groundwater contamination. From experience and research carried out at landfills, these proposals have been tested and evaluated. The science is, however, a rapidly developing one which is extremely complex owing to its multi-disciplinary nature.

Research into approaches and methods of preventing groundwater contamination by waste disposal activities is currently receiving attention from both the WRC and DWAF (DWAF, 1994a, 1994b; Parsons and Jolly, 1991; Levin and Verhagen, 1990; Meyer et al., 1990; Murphy, 1990). As a result, the standards and practices applicable to the waste management arena in this country are continually evolving and improving. However, from this work it became increasingly clear that an area of research that needed urgent attention was that of groundwater recharge and leachate generation at waste disposal sites.

From a geohydrological point of view, it is relatively simple to show that groundwater recharge occurs throughout the country, irrespective of climatic conditions (Kok, 1991). The quantification of recharge is however far more difficult, as shown by local research carried out by Kirchner et al. (1991), Fleisher (1990), Bredenkamp (1987) and others. It is well understood that recharge is caused by specific rainfall events, usually above a certain threshold. Owing to a lack of country-wide quantified information on recharge, *a percentage of MAP* is often used to provide a rough indication of the volume of rainwater that reaches an aquifer.

The classical Waste Site Water Balance method (WSWB), on the other hand, has been widely applied in South Africa to determine or predict leachate generation at waste disposal sites (Jewaskiewitz, 1992; Howard and M^cGee, 1991; Blight et al., 1990; Lombard, 1990; Hojem, 1989). These estimations are usually based on either annual averages or six monthly seasonal averages. "Regarding precipitation, it has become generally accepted that in areas where the annual evapotranspiration rate exceeds the annual precipitation rate, ie. water deficit climates, water contamination due to landfill leachate is not a problem." (Ball, 1984, p. 16). This suggests that leachate only poses a threat to groundwater in 20 % of South Africa. Further, a preliminary study "produced strong evidence that if climatic conditions are such that a perpetual water deficit exists at the site of a landfill, no or very little leachate will be formed or exit the base of the landfill (Blight et al., 1990, p. B2).

Both aquifer recharge and leachate generation estimation techniques aim to simplify an extremely complex process. Further, both approaches are primarily based on climatic considerations, yet yield apparently contradictory results. On the one hand, it is accepted that aquifers are recharged throughout the country while on the other hand it is accepted that leachate generation only poses a threat to aquifers in 20 % of South Africa. If the former approach is correct, all aquifers are threatened to some degree by waste disposal activities. If the latter premise is accepted, groundwater contamination at waste disposal sites would not be considered to be a problem in the drier parts of South Africa.

Early research into this paradox indicated that South Africa is not unique with regard to the application of the WSWB method. For example, Knox (1992, *pers.comm.*), as part of a major Department of Environment (UK) study, could not find one detailed investigation where leachate prediction by means of the water balance was correlated with actual rainfall. However he identified a large amount of literature in which the water balance method was applied for a variety of purposes, including landfill siting and determining co-disposal rates.

During 1991, a project entitled *Minimum Requirements for Waste Disposal by Landfill* was initiated by DWAF which aimed to set minimum requirements for waste disposal in South Africa. These guidelines and standards are considered to be forerunners to modifying and improving waste disposal legislation and DWAF policy. An early draft of the project report (Ball et al., 1992) proposed a landfill classification system, partially based on the Climatic Water Balance (CWB). The CWB was defined as follows:

$$B = R - E$$

*Where* $B$ = *water balance*
$R$ = *rainfall*
$E$ = *potential evaporation X 0.7*

If B is negative, then little or no leachate would be generated on a regular basis and leachate management would not be required. A positive B would point to leachate being generated on a regular basis and leachate management being required. These two cases were respectively designated as *no leachate* (Nl) or *leachate management required* (Lm).

The apparent paradox between the recharge and WSWB approaches, the widespread acceptance and application of the classical WSWB method to predict leachate generation and the proposal to use the CWB to define minimum requirements at waste disposal sites prompted the author to approach the WRC for funding so that situation with respect to the two approaches could be investigated. It was argued that should the basis of the water balance technique prove to be incorrect or invalid, it could result in less stringent legal requirements being set for major parts of semi-arid South Africa than should be the case.

## 1.2. Research Objectives

The objectives of the research project are to evaluate approaches employed locally and internationally to determine *recharge* and *leachate generation*. Such an independent investigation should provide detailed scientific insight into the problem so that the more appropriate approach can be identified. Should the classical WSWB method be found to be more appropriate, it would lend credibility to the waste site classification system. Conversely, should the groundwater recharge approach be found to be more applicable, modifications could be made to the Minimum Requirements before general implementation.

The objectives of the research project are, therefore, as follows:

a. to assess approaches and methodologies employed internationally to determine rates of recharge and leachate generation at waste disposal sites.
b. to assess approaches and methodologies employed in South Africa to determine rates of recharge and leachate generation at waste disposal sites.
c. to compare the approaches and methods identified in (a) and (b) in order to evaluate the current knowledge and practices in South Africa.
d. to identify further research needs in this field in South Africa.

## 1.3. Research Method

The research was carried out by means of a detailed literature study and discussions with selected proponents of the two approaches. International approaches and methods were studied in order to assess current world-wide practices. Local literature was assessed to determine South African practice.

Discussions were held with South African experts from both schools of thought. An attempt was made to speak to at least one expert from each discipline involved in waste and groundwater protection (ie. waste management, site engineering, soil science, geohydrology).

A short course entitled "An introduction to microbiology of landfills and landfill gas" was also attended. The course formed part of the Continuing Engineering Education Programme of the University of Witwatersrand and was presented during November 1992.

Mr Andrew Stone of the American Ground Water Trust, and an authority in the field of groundwater contamination and protection, was appointed to investigate current practice and approaches used in America with regard to waste management, leachate generation and groundwater contamination. This was carried out through a process of personal discussions, literature evaluation and accessing various databases. His report is included as Appendix A in order to provide a perspective of current American trends in the fields of leachate generation, landfill management and groundwater protection.

The project was carried out over a 9 month period. This report represents the completion of the literature-based project.

It must be noted that even though the Minimum Requirements project (DWAF, 1994) helped precipitate this research effort, the Minimum Requirements project was not the focus of this study. The Minimum Requirements project was still in a state of on-going development during this investigation and hence no final decisions or proposals had been tabled.

## 1.4. Report Structure

Following the introductory chapter in which the problem statement is presented, the topics of leachate generation and the classical WSWB method (Chapter 2) and groundwater recharge (Chapter 3) are addressed. The theory behind the methods, the factors which control leachate production and recharge as well as the methods of calculation are introduced prior to listing some important case studies and the limitations of each approach. In Chapter 4, the similarities and differences between the two approaches are discussed in terms of their ability to accurately predict output ie. the volume of leachate generated or the volume of water which recharges an aquifer. Conclusions and recommendations are presented in Chapter 5.

# 2. LEACHATE GENERATION

## 2.1. Introduction

Leachate is generated as a result of the percolation of water or other liquid through any waste and by the squeezing of the waste due to its weight (Bagchi, 1990). Thus, leachate can be defined as a liquid that is formed when water or another liquid comes into contact with waste. It is a highly contaminated, aqueous solution which carries in it dissolved solids and the final and intermediate products of decomposition (Ball, 1984). In this study only the *quantity* of leachate generated is addressed. Reviews of the quality of leachate are provided by Robinson and Gronow (1992), Ross (1990), Farquhar (1989); Ham (1988) and Ehrig (1984).

The classical Waste Site Water Balance (WSWB) method attempts to predict the *volume* of leachate that will be produced by a waste site. The method is based on the principle of conservation of mass and assumes that the system is closed. It is basically a moisture budgeting approach. The mass of water entering the system must equal the mass of water leaving the system plus the mass of water retained in the system. The implication of the method is that low annual average precipitation will be insufficient to produce leachate.

The WSWB method is applied widely throughout the world in its various forms (Anderson et al., 1993; Jewaskiewitz, 1992; Mattravers and Robinson, 1991; Hojem, 1990; Krantz and Bailey, 1990; Ball et al., 1987; Shimell, 1986). The method is used for a number of different purposes, including:

a. determining or predicting leachate generation rates
b. defining waste site design and management requirements
c. determining acceptable solid and liquid co-disposal rates
d. waste site classification purposes

Its world-wide acceptance is, however, open to debate. For example, Lee and Jones (1991 - as quoted by Stone, 1993), respected American contaminant hydrogeologists, noted that it is invalid to suggest that because the regional net water balance is negative, no leachate will be generated. Knox (1991), in his review of the WSWB methods applied in the U.K., frequently recorded a high degree of scepticism expressed about the accuracy of water balance calculations. He attributed this in part to the great variability and very wide range of values of absorptive capacity presented in the literature or measured in the field. Shimell (1986) stated that the water balance is one of the most controversial topics in landfill management in Britain. Unfortunately she did not go into specific details.

One of the major difficulties in the assessment of the validity of the WSWB method is the lack of reasonably accurately measured leachate generation data from waste sites. Investigations at laboratory, lysimeter or test plot scale abound both locally (Chapman and Ekama, 1992; Novella and Ross, 1992; Blight, 1992 and Hojem, 1988) and internationally (Reitzel et al., 1991; Nyhan et al., 1990; Watson-Craik and Senior, 1989; Peyton and

Schroeder, 1988; Korfiatis and Demetracopoulos, 1986; Ross, 1985 and Collins and Spillmann, 1982), but little data concerning actual full-scale landfill leachate generation is available with which to verify WSWB computations. This was also the case reported by Stone (1993) in America and Knox (1991) in the United Kingdom. Robinson (1990) and Robinson and Grantham (1988) provided measured estimates of the volume of leachate treated which, in turn, could be an indication of leachate generated. Ehrig (1984) provided data on leachate generation measured in Germany. However, this sort of data is very much the exception. Also, no leachate generation data from arid or semiarid areas was identified during this literature study.

It is important to remember, however, that the WSWB method attempts to model a highly complex and dynamic situation using a simple, easy-to-use and rapid method. As such the method has to make a number of simplifications and assumptions concerning the leachate generation process. In considering some of the methods and their input parameters in the following sections, assumptions and simplifications will be identified.

## 2.2. Generalised Theory

The theory behind the classical WSWB method is well documented. Good comprehensive reviews of the literature are presented by Blight (1992), Knox (1991), Lisk (1991) and Hojem (1988). As such, continual reference is made to these documents in this report. This chapter will only give a broad overview of the theory and will concentrate on some of the more critical considerations. The WSWB method is based on the following:

*leachate generation = water input - water losses ± change in storage*

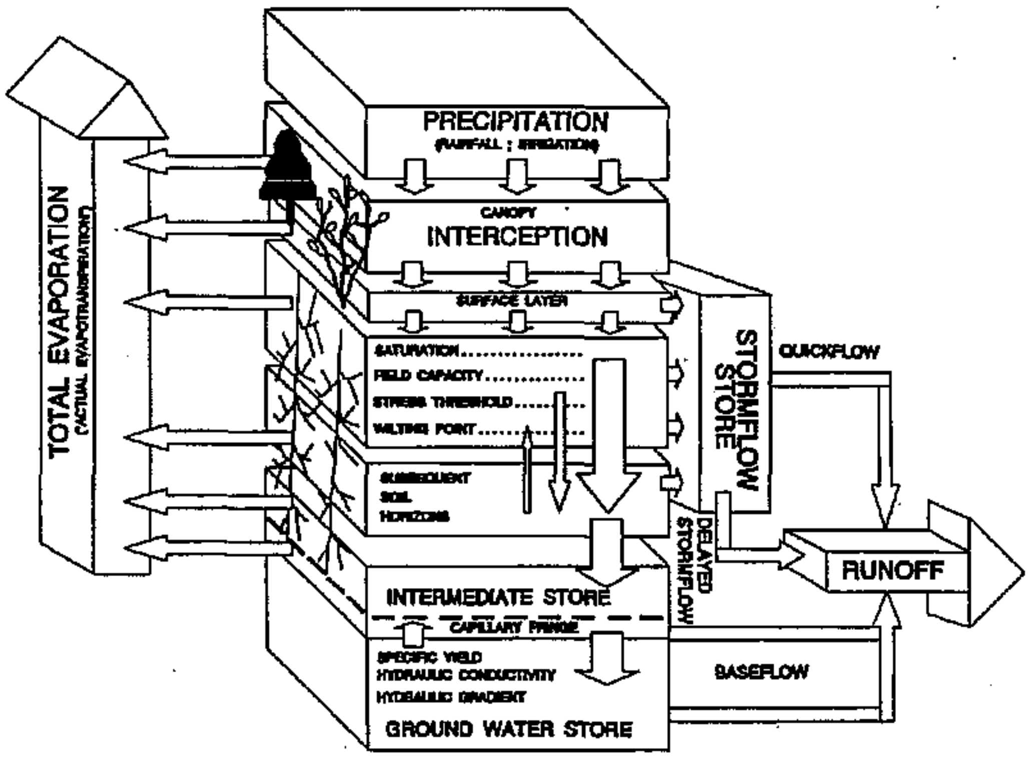
If the individual parameters are regarded, then the generalised WSWB equation can be expressed as:

$$L = (P + W_m + B) - (R + Et + G) \pm \Delta S$$

| | | | |
|---|---|---|---|
| *where:* | $L$ | = | *leachate generation* |
| | $P$ | = | *precipitation* |
| | $W_m$ | = | *initial moisture content of the waste* |
| | $B$ | = | *chemical and biological water production* |
| | $R$ | = | *run-off* |
| | $Et$ | = | *evapotranspiration* |
| | $G$ | = | *vapour loss in gas* |
| | $\Delta S$ | = | *change in storage* |

A number of variations of the general equation can be found in the literature. In some cases it is merely the terminology that varies. In other cases, however, the equation is either expanded to contain more parameters or simplified by making assumptions relating to the relative importance of particular parameters. The CWB method proposed by Ball et al. (1992, Section 1.1) is an example of the latter.

For the purpose of illustrating the processes and components of water entering and leaving a system, a graphic representation of the ACRU model is presented (Figure 1). The model is a multi-purpose, multi-layer soil-water budgeting system based on physical conceptual principles, with a wide range of capabilities (Kienzle and Schulze, 1992). The model was not developed nor has it been modified to be able to predict the volume of leachate generated. It can however be regarded as the soil science equivalent of the WSWB method, of which a simplified graphical representation is provided in Figure 2.




(Kienzle and Schulze, 1992)

Figure 1: A graphic representation of the ACRU Model.

## 2.3. Factors Controlling Leachate Generation

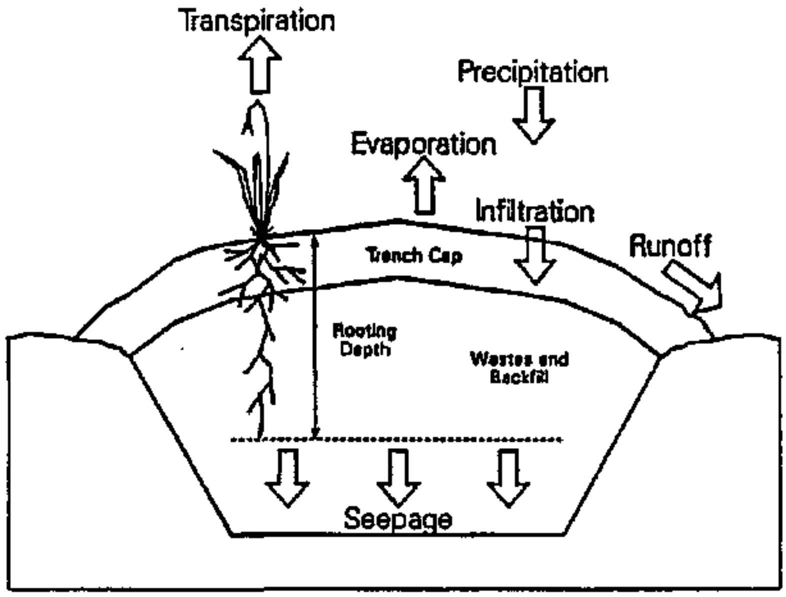
### 2.3.1. Precipitation

Precipitation includes rain, hail, sleet and snow. In a South African context, only rainfall is of general significance. "The input from rainfall is commonly the largest single input to the water balance of a landfill. In many cases it is the **only** liquid input, and in all cases it is likely to be of major significance" (Knox, 1991, p. 132).

Hojem (1988) noted that the measurement of rainfall is probably the easiest of all the elements in the water balance. This does not, however, signify that the measurement is without inaccuracies. Factors which impact on measurement include:

a. the position of the rain gauge in relation to obstructions such as mountains, buildings, trees etc. (which cause eddying and splash-induced inaccuracies)
b. the height of the rain gauge above ground
c. the location of the rain gauge relative to the waste facility

Rainfall can vary considerably over short distances. The extrapolation of data from one point to another can lead to errors and uncertainty. Viessman (as quoted by Knox, 1991) found that differences of up to 20 % were recorded by two rain gauges located 6 m apart. Knox (1991) estimated that poorly sited rain gauges and data extrapolation over some distance can account for errors of 10% in annual data and up to 20% in event-specific data.




(Nyhan et al., 1990)

Figure 2: A graphic representation of the WSWB method.

In considering input into the WSWB equation, the nature of the precipitation has to be considered as well as what happens to the precipitation once it hits the surface. Rainfall pattern appears to be an important consideration (Stone, 1993; Kienzle, 1993 *pers.comm.*; Blight, 1992; Ham, 1988; Hojem, 1988). In terms of the nature of rainfall, it is accepted that high intensity storms promote run-off since intensity generally exceeds rate of infiltration. During events of lower intensity, intensity is lower than infiltration rate and most of the water can enter the subsurface. This will continue until saturation is reached. The antecedent moisture conditions are important in controlling how much rainfall enters the ground before saturation occurs.

The pattern of rainfall through the year also plays a role in determining infiltration. Shimell (1986) reported a case, where even though rainfall was higher during a particular year, infiltration was lower than that recorded during preceding years. This phenomenon was ascribed to the bulk of the rain falling during summer instead of during winter, as was usually the case.

As rain hits the surface, the water can either run-off over the surface or infiltrate into the subsurface. These two components of the hydrological cycle are reviewed below.

### 2.3.2. Run-off

The term *drainage* is often used interchangeably with run-off. By definition, run-off is that part of rainfall which does not infiltrate the earth's surface nor is lost through evapotranspiration. Run-off is one of the few factors that can easily be controlled with good site management. With proper design and management, run-off can be prevented from entering the site while run-off can be promoted on-site using a low permeability, sloped cover. It, nonetheless, still needs to be considered in the overall water balance.

Run-off can occur by two mechanisms, namely overland flow or interflow. Overland flow occurs when rainfall intensity exceeds infiltration capacity while interflow is that flow which cannot infiltrate vertically and thus flows horizontally at or near the surface in the soil zone. The nature of flow appears to be a function of soil type and rainfall pattern.

Knox (1991) notes that few workers consider run-off when applying the water balance approach. If it is considered, generalised assumptions and run-off coefficients (expressed as some percentage of rainfall) rather than actual field measurements are used. This could be related to the funds and time available to determine the information accurately.

Run-off can be estimated using a number of approaches, the two most common are the rational method (Shaw, 1983) and the curve number method developed by the United States Department of Agriculture Soil Conservation Services (Schmidt and Schulze, 1987). The second method is commonly referred to as the SCS method. The SCS method does consider antecedent soil moisture conditions in coarse categories.

The rational method does not consider antecedent moisture conditions or changing infiltration capacity. It is simple to apply but is known to have a great margin of error (Blight, 1992). The principal difficulty appears to relate to C, an empirical factor related to the type and slope of the run-off surface.

Lerner et al. (1990) noted that it is possible to quantify run-off by comparing infiltration rate to the intensity of individual precipitation events. Besides being simplistic in approach and not considering temporal changes resulting from changing moisture conditions, the analysis is lengthy and intricate.

### 2.3.3. Infiltration

Infiltration and percolation are used interchangeably in the literature. In this study infiltration is reserved to describe *water entering the earth's surface* from the atmosphere. Percolation is used to describe *water moving downwards in the waste pile*, mainly due to gravity.

In considering the volume of water that enters a waste pile, and hence contributes to leachate generation, that part of rainfall which infiltrates is far more important than precipitation *per se*.

Infiltration and the rate of infiltration are governed principally by the nature of the material, the volume and intensity of precipitation and antecedent moisture content. All three of these components are dynamic. The role of precipitation type and antecedent conditions were outlined in Section 2.3.1. Infiltration at waste facilities is promoted by ponding, surface cracking, surface erosion and uncovered waste. The properties of the surface cover thus need to be considered. In measuring the infiltration rate at Linbro Park, Blight (1992) found a great difference in the results obtained. She found that results varied from site to site and test to test. She partly ascribed this to antecedent moisture conditions and the presence of cracks in the cover. Because of these considerations, infiltration differs from day to day and from event to event. Shimell (1986) reported similar findings. It is thus extremely difficult to estimate infiltration with any confidence.

Much of landfill design and management is aimed at reducing infiltration. Landfill caps and cover are made of low permeability material so that the volume of moisture infiltrating into the waste pile is reduced (Blight, 1992; Richardson, 1992; Bagchi, 1990). As such, these design and management aspects need to be considered in any water balance approach.

The *in situ* measurement of infiltration at waste disposal sites is possible (Daniel, 1987) and is often done using infiltrometer or percolation tests. If performed correctly, these tests usually reflect saturated conditions under a specific head and thus *represent the slowest rate of infiltration*. If the initial infiltration rate measured during a test is used, then a degree of variance, which can be directly ascribed to antecedent moisture, can be expected. All *in situ* tests are, however, subject to limitations (Chen and Yamamoto, 1987). Laboratory experiments are also used to estimate infiltration. The representativeness of the results remains a problem owing to the disturbance of the material during sampling, sample preparation and confining stress (Daniel, 1987).

### 2.3.4. Initial Moisture Content of Waste

Collins and Spillmann (1982) found that the initial waste moisture content was an important component of the water balance in that low moisture contents delayed the start of leachate production. The initial moisture content of waste depends largely on the type of waste being disposed of. Paper, ash and glass, for example, have a low initial moisture content while that of food waste and garden refuse is high (Blight, 1992). The initial moisture content of waste, particularly domestic refuse, should accordingly be expected to be highly variable.

The term *co-disposal* refers either to the mixing of "hazardous" with "non hazardous" wastes or mixing solid waste with liquid wastes. It is proposed that a convention be adopted by indicating in brackets which meaning is applicable ie. co-disposal (hazardous / non hazardous) or co-disposal (solid / liquid). The term *co-disposal (hazardous / non hazardous)*, however, should be treated with some caution as domestic waste contains elements of all waste types (Uehling, 1993; Suflita et al., 1992; Stone, 1991). The concept of co-disposal (solid / liquid) is popular (Novella and Ross, 1992; Watson-Craik and Senior, 1989; Ham, 1988) and is based on the understanding that waste sites have spare moisture holding capacity in situations where evapotranspiration is greater than precipitation. The WSWB method is used to determine hydraulic loading rates ie. how much sewage sludge, for example, can be mixed with domestic refuse before leachate is generated.

The measurement of a representative waste moisture content for a landfill has been found to be difficult. Lisk (1991) stated that waste is extremely heterogeneous and, as such, it is difficult to collect representative samples for analysis. It is also almost impossible to measure or predict the volumes of liquid being disposed of, either wilfully or otherwise, in the municipal waste stream. The disposal of paints, oils, thinners, detergents and batteries in domestic waste, for example, certainly allows for an unhealthy toxic cocktail.

Consideration of initial moisture content was discussed in the literature, but seldom was this component considered in the application of the WSWB. Letcher (1990) and Hojem (1988) estimated that the initial moisture content could be in the order of 20 % (dry mass basis). This is approximately a third of the commonly reported field capacity of waste. Should initial moisture content be ignored, significant underestimates of leachate production could result.

### 2.3.5. Moisture Resulting From Waste Decomposition

Waste decomposition and landfill gas production may cause both the production and consumption of moisture in a landfill. The production of water results from some chemical reactions (Bagchi, 1990; Letcher et al., 1988) while water consumption is related largely to biological decomposition and vapour losses (Senior, 1991; Hojem, 1988). No definitive or quantified information could be obtained from the literature concerning this aspect.

The generation of landfill gas occurs in two distinct phases. During the aerobic phase, heat, carbon dioxide and water are produced. Leachate is characterised by a high COD and by its slightly acidic nature. However, these processes are of very minor importance as this phase lasts for a relatively short period (Blight, 1992; Knox, 1991). Landfills tend to become fully anaerobic within a few weeks of waste emplacement.

The aerobic phase is followed by the acid anaerobic and methanogenic anaerobic phases. The major portion of waste degradation then involves the anaerobic fermentation of cellulose which proceeds through several distinct bacterial stages to complete methanogenesis. Here methane and carbon dioxide are the end products of degradation. Hojem (1988) noted that the leachate produced during the acid phase is characterised by a low pH and a high COD. During methanogenesis, high pH and low COD are typical.

Knox (1991) argued that during the anaerobic phase, a net consumption of water occurs.

Using the Buswell equation and making some theoretical assumptions, he estimated that approximately 27 L of water is consumed per ton of waste at a rate of about 1.34 L/t.a.

In the past it was generally accepted that the biodegradation of wastes was promoted under specific conditions. The moisture content of the waste is but one consideration. It was previously argued that biodegradation is promoted at specific moisture contents (Ross, 1990; Ham, 1988). Following the archaeological investigation of the Fresh Kills waste site in New York, where it was found that biodegradation was not as effective as was first thought (Rathje, 1991), considerable attention is now being focused on this aspect. It is now proposed that waste facilities be kept as moist as possible (Uehling, 1993). This is in fact the Danish approach and was previously advocated by Jorgensen (1987 - as quoted by Hojem, 1988).

Suflita et al. (1992) found that measured methane gas yields are typically only between 1 and 50 % of that theoretically possible. This inhibition could be due to a number of factors:

a. the presence of sulphate
b. the limitations imposed by moisture content
c. the heat in the landfill killing microorganisms and partially sanitising the landfill and reducing biodegradation

Further, Chapman and Ekama (1992) found that the onset of methanogenesis in the landfill is inhibited by high organic acid concentrations. Suflita et al. (1992, p. 1493) concluded that "our expectations of microbiological decompositions are unrealistic." In light of no direct experimental evidence regarding water production or consumption in the waste pile being available (Knox, 1991), assumptions concerning this component are made. Some argue that water production could be significant (Senior, 1991) while others such as Blight (1992) have noted that the volume of water produced by chemical and biological reactions can be assumed to be small.

No examples were found in the literature in which moisture from waste decomposition was quantitatively considered in the application of the WSWB method. The general consensus appeared to be that this component could be ignored. Until such time as more definitive information is available, this assumption must be regarded as a possible source of error in the water balance.

### 2.3.6. Lateral Inflow

A component not usually considered as a source of water in the WSWB method is lateral groundwater inflow. This could be caused by either extreme events or prevailing geohydrological conditions. It was common practice, for example, to place waste facilities in old quarries where the base of the site was often below the groundwater level. This resulted in the waste at the base of the pile being submerged in water. *It is in such circumstances that poor siting of the landfill contributes to leachate generation* (DWAF, 1994a).

Lateral inflow (and outflow) need only be considered in specific situations. The case studies examined in this review did not, in general, consider this aspect.

## 2.3.7. Evapotranspiration

For the purpose of this study the term *evapotranspiration* will be used to include both *evaporation* and *transpiration* components. It is nonetheless recognised that, from a waste management perspective, evaporation is probably of greater significance than transpiration. Limited vegetation is found on waste piles, particularly before site closure and rehabilitation. Plants and trees are, however, used as an engineering strategy to reduce the potential for leachate generation at waste sites (Anderson et al., 1993).

Distinction has to be made between actual and potential evapotranspiration. Knox (1991) noted that in cases the actual rate of evapotranspiration fell below the potential rate of evapotranspiration. Bagchi (1990) argued, on the other hand, that in the design of a landfill, the potential evaporation is of more importance.

The evapotranspiration element in the WSWB method is arguably the most difficult element to quantify with any confidence. It is impacted upon by, amongst others, temperature, wind, atmospheric pressure, daylight hours, sunshine hours, topography, solar radiation, albedo, dissolved solids, vegetation and the nature of a surface. A number of methods and equations are available for estimating potential evapotranspiration rate. These include the Blaney-Morin equation, the Thornthwaite equation, the Thornthwaite and Mather equation, the Penman equation, the Turc equation, the Christiansen equation and the Blaney-Criddle equation.

### 2.3.7.1. Potential evapotranspiration

Potential evapotranspiration is generally estimated using two methods, namely the Penman or Thornthwaite methods (Knox, 1991). The former method was first developed by Penman in 1948 and has subsequently been modified. The method is widely used in both Europe and America and forms the basis of the HELP model. It is based on the absorption of radiation energy by the ground surface.

The Thornthwaite method was developed by Thornthwaite in 1954. It was later modified in 1957 by Thornthwaite and Mather. It is still widely used, particularly in America, were it is often used in preference to the Penman method. It is based on the exponential relationship between mean monthly temperature and a mean monthly heat index. The Thornthwaite method is far simpler than the Penman method and is less dependent on physical variables. Mean air temperature and hours of daylight are used instead.

The Penman-Monteith method is complex and incorporates many of the physical variables which affect potential evapotranspiration (wind speed, albedo, temperature, solar radiation, vegetation coverage and vegetation type). A limitation in applying the method is that many weather stations do not measure many of the parameters required (Blight, 1992). Because of its use of several physical variables, the method is sensitive to changes in values of the input data (Knox, 1991). For example a change in albedo from 0.25 (grass-covered areas) to 0.1 (bare soil) leads to a 19% increase in estimated potential evapotranspiration.

Knox (1991) presented different values of potential evaporation determined using the two methods. Even though the annual totals were similar, large differences were recorded for monthly data (up to 55%). He found no evidence, however, to suggest which was the more accurate method. He warned that, in the U.K., errors ranging between 10% and 25% should be assumed in annual calculations while monthly estimates may be erroneous by as much as 35 %.

### 2.3.7.2. Actual evapotranspiration

Actual evaporation is a measure of the depth or volume of water that is lost through the evaporation process. It is particularly difficult to estimate, particularly if the question of whether pan evaporation equates to soil evaporation is addressed. Knox (1991) noted that many methods have been developed to determine actual evapotranspiration, most of which were developed for agricultural soils and aim to predict the soil moisture deficit (SMD). Models include ESMD (Estimated Soil Moisture Deficit) and MORECS (Meteorological Office Rainfall and Evaporation Calculation System). Significantly different results are yielded by the two methods. Problems related to the use of these two methods at waste sites include:

a. defining under what conditions potential exceeds actual evapotranspiration.
b. lack of calibration for both active and restored landfills.
c. ESMD uses monthly data while MORECS is based on actual daily measurements
d. neither model considers short-circuiting.

With respect to short-circuiting (also referred to as preferential flow paths), the models assume that the downward percolation cannot occur until SMD is satisfied and the soil is at field capacity. Any rain infiltrating while a SMD exists is assumed to be taken up firstly in reducing the SMD. "It has long been known from field observations that this does not always hold true for either soils or for solid wastes. During heavy rains, particularly during summer, short-circuiting of a proportion of the rain can occur, even when a significant SMD exists" (Knox 1991, p. 138). Rushton and Ward (1979, cited in Knox, 1991) investigated several empirical expressions in an attempt to model observed short-circuiting. They proposed the following equation to calculate the amount of rainfall routed directly to recharge in north Lincolnshire :

$$15\%\ P\ (\text{for } P > 5\ mm/d) + 15\%\ ER'$$

| | | | |
|---|---|---|---|
| *where* | *P* | = | *total rainfall* |
| | *ER* | = | *effective rainfall and is determined by subtracting actual evaporation from the rainfall* before *making up any SMD* |

Lysimeters have also been used in attempts to measure evapotranspiration directly. The method is expensive and is not accurate (Blight, 1992).

A pragmatic approach to the approximation of actual evapotranspiration is to measure evaporation in a standard evaporation measuring pan and then to apply the following formula to the data (Hojem, 1988):

$$E_a = E_m \times 0.7.$$

| | | | |
|---|---|---|---|
| *where:* | $E_a$ | = | *actual evaporation* |
| | $E_m$ | = | *measured pan evaporation using a standard evaporation pan* |
| | *0.7* | = | *correction coefficient based on the work of Schulze (1974) and Gray (1973), as quoted by Hojem (1988).* |

Hojem (1988) applied 7 different methods of estimating potential evaporation to data from the Linbro Park waste disposal site. Estimations ranged from 596 to 1509 mm/a. Using annual rainfall data, only the Turc and Penman methods predicted a water surplus situation. Hojem recognised that water surplus situations could occur seasonally during the year. He stated that in such cases a daily balance would be more appropriate than weekly and monthly estimations. He then applied the Thornthwaite and Mather method to daily, weekly and monthly data. He found large differences in the predicted percolation depths. For example, where a cover of 200 mm was assumed, percolation predictions varied from 0 to 301 mm/a. Hojem concluded from this work that it was difficult to predict percolation (and hence leachate generation) with any confidence.

Evapotranspiration is recognised in the literature as the single biggest component of water loss. It was also found to be the most difficult to measure or estimate. Further, small changes to the estimated value used in the various methods tend to have a significant impact on the final estimated leachate generation (Nyhan et al., 1990). Two of the issues raised in the literature are briefly outlined below:

- the evapotranspiration at field capacity and the evapotranspiration at wilting point will be different due to the availability of water and the suction between the waste and water. Antecedent moisture conditions thus play a role. Blight (1992) referred to the constant rate stage of evaporation, the falling rate stage and the slow stage. Evapotranspiration is hence dynamic with time and needs to be considered on small time steps.

- the depth to which evaporation (and evapotranspiration) is effective is discussed by a number of authors (eg. Anderson et al., 1993; Blight, 1992). Even though this is a relevant and possibly even a critical issue, a detailed examination of this problem is beyond the scope of this treatise. Effective evaporation depths appear to be in the order of a few meters rather than centimetres.

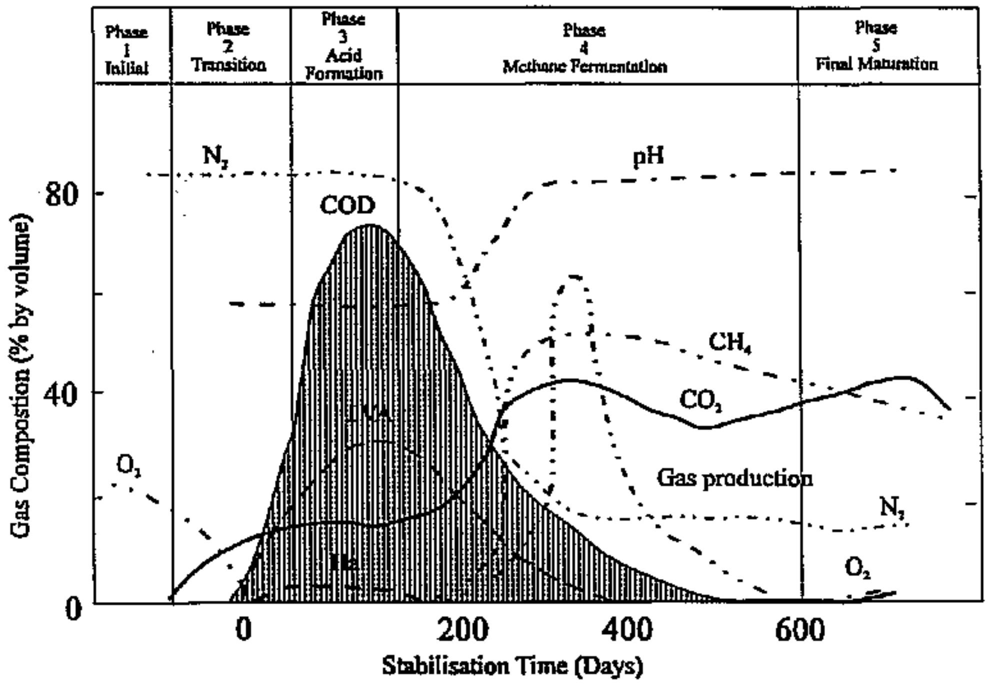
It was interesting to note during this review that Peyton and Schroeder (1988) could not find suitable evapotranspiration field data from landfills to use in their field verification and calibration of HELP. They noted that this was due to the complexities involved in collecting this sort of data. They also recognised that evapotranspiration is the single largest outflow component of the landfill system.

The problems associated with obtaining reliable and accurate evapotranspiration data is seen as one of the major problems in the application of the WSWB method. This is particularly true as most leachate generation methods are sensitive to small changes to the model input value. The dynamic nature of evapotranspiration also needs to be accounted for in more detail.

### 2.3.8. Vapour Losses in Gas

This component of the WSWB method was usually included in the general discussion concerning the method. Its inclusion in actual calculations was found to be limited. Knox (1991) noted that gas leaving landfills is usually saturated with water vapour. The content appears to be directly related to the temperature of the gas. As much as 10 L/t could be lost in this way at a rate of about 0.5 L/t.a. If it is considered that the consumption of water occurs over several decades, then the rate of loss is more significant than the total volume. Knox explained that it was thus conceivable that a landfill could dry with time as a result of decomposition.

If the now classical diagram of landfill gas is considered (Figure 3), the volumes of water lost from the waste pile through vapour can be expected to be small.




(After Pohland et al., 1983)

Figure 3: Landfill gas production patterns.

### 2.3.9. Storage of Water in the Waste

The storage of water in the waste pile, and the dynamics thereof, are extremely complex. They are also central to the WSWB approach. A number of inter-related concepts and parameters need to be considered. Of all the components of the WSWB method, it is this component which requires the greatest exchange of knowledge and understanding between the disciplines of engineering, soil science and hydrogeology.

### 2.3.9.1. Heterogeneity

One aspect that was found common to all literature was that waste is extremely heterogeneous. Heterogeneity makes it difficult to determine and define parameter values and, as such, results in limitations in the application of the WSWB method. Evidence suggests that the uptake and release of water by waste may be even more complicated than that by soil. For example, field capacity is defined as the maximum amount of moisture that waste can retain against the pull of gravity when allowed to drain freely. The term is relatively simple to envisage when applied to soils. With waste it is more difficult - a piece of plastic, for example, could trap water and hence retain free liquid indefinitely, even when allowed to drain freely.

The heterogeneity of a waste pile is further depicted by considering the contents of a pile. At opposite ends of the material scale are cover material (clay, sand or soils) and waste which includes paper, glass and organic material. The proportion of material present at any one point in the waste pile varies considerably. The assignment of a single, representative value for any hydraulic property of the waste is thus extremely difficult, if not impossible.

The concept of heterogeneity has to be considered in terms of scale. On a small or micro scale, the above comments hold true. This is also the case when considering fractured aquifers. On a macro or larger scale, the waste pile can be considered to be homogeneous in nature.

### 2.3.9.2. Terminology

A complicating factor when addressing waste properties in the context of moisture content is the incorrect or inconsistent use of terminology. Knox (1991) states that the storage of moisture by waste has been compared directly to that by soil. The incorrect or inconsistent adoption of soil science terminology by the waste community has led to confusion. However Knox is also guilty of creating some of this confusion. For example, he defines *saturated storage coefficient* as:

> *the difference in the amount of moisture held by the waste at field capacity and that held by the waste when it is saturated.*

Driscoll (1986), in addressing aquifer properties, defines *storage coefficient* as:

> *the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.*

Great care needs to be given to the proper use and adoption of terminology and the definitions involved, particularly when working in a multi-disciplinary field such as waste management.

### 2.3.9.3. Properties

In addressing the water held in storage by waste and the dynamics thereof, a number of the hydraulic properties of the waste need to be appraised. These include:

a. moisture content
b. porosity (and density)
c. capillarity
d. field capacity
e. SMD
f. storage
g. hydraulic conductivity

a. The concept of initial moisture content and the measurement thereof was previously discussed in Section 2.3.4. and need not be expanded further.

b. Porosity is defined as *the percentage of the bulk volume of a rock (or soil or waste) that is occupied by interstices, whether isolated or connected* (Driscoll, 1986). However, not all water held in the voids can be removed from that material. Some water is included in the composition of the material and is hence fixed. Other water is bonded onto the material by suction or matric forces *(matric or capillary water)*. Strong suctional forces are required to overcome the attractive forces. The final type of stored water is that in the voids which is easily drained by gravitational forces *(gravitational waters)*. On compaction, the density of material is increased. This impacts on the storage and transmitting properties of the material. It can be expected that the water storage properties would be reduced upon compaction.

c. Suction forces between the material and water are responsible for capillarity. Capillary movement was found to be important by Nyhan et al. (1990) in that it provided a mechanism for upward flow. In contrast, Ehrig (1984) noted that the capillarity of refuse is very low and this prevents an upward flow of water which could then be subjected to evaporation.

d. In terms of the WSWB method and the prediction of leachate generation, field capacity is probably the most important property of waste. It is defined by Pitty (1979, p. 130) as:

> *the amount of water which is retained in the soil after free gravity water has drained from the soil.*

e. Coupled with the concept of field capacity is the concept of SMD, which can be expressed as *the difference between actual moisture content and field capacity*. In other words, SMD is the amount of additional water that a body could store without the occurrence of gravitational flow. Knox (1991) and Watson-Craik (1987) referred to this as absorptive capacity.

Theoretically, waste can absorb a certain volume of water (Bagchi, 1990), but the absorption of water by waste is not uniform. The difference in absorptive capacities is highlighted by figures presented by Knox (1991). The absorptive capacities are (% dry weight):

| | |
|---|---|
| glossy magazine | 100 |
| solid and corrugated cardboard | 160 |
| newsprint | 300 |
| paper towel | 450 |
| toilet tissue | 700 |

From the literature Bagchi (1990) found that initial moisture content of waste was in the order of 12 % while field capacity was set at 35 %. The determined absorptive capacity was thus 23 %.

"The available data on absorptive capacity exhibit great variability and present a very wide range of values. This is undoubtably in part responsible for the high degree of scepticism frequently expressed about the accuracy of water balance calculations." (Knox, 1991, p. 166).

Absorptive capacity depends on the initial moisture content, type of waste, compaction and waste density and waste age. Knox (1991) found that reported data usually came from a small part of the spectrum (ie. fresh domestic waste compacted to low densities) and that most data were generated coincidently from studying co-disposal or waste decomposition. He noted that, based on this observation, there is a great need to study waste characteristics. A similar call has been made by Hojem (1988).

The apparent spare capacity to store additional water is used to define hydraulic loading rates in the practice of co-disposal (Novella and Ross, 1992; Watson-Craik, 1987). It also forms the basis of calculating when leachate will be generated (Blight et al., 1992; Hojem, 1990). The WSWB method intrinsically assumes that leachate will not be generated prior to field capacity being reached. Blight (1992) refers to this as the "Tank Model" in which the tank has to fill up to field capacity before moisture can leave the tank through vertical or horizontal water flow. The validity of the "Tank Model" or the fact that leachate will not be generated before SMD is satisfied is seriously questioned. Many authors have found that leachate and leachate flow is detected prior to the attainment of field capacity (Stone, 1993; Novella and Ross, 1992; Blight, 1992; Hojem, 1988; Watson-Craik, 1987; Collins and Spillmann, 1982; Stegman, 1982). This could be due to:

- an incorrect assumption or estimation of field capacity
- a change of field capacity with time, probably due to compaction and settling
- existence of preferential flow paths in the waste pile.
- unsaturated flow.

There is sufficient evidence in the literature to show that the concept of field capacity having to be reached before leachate can be generated is false. The use of the WSWB method to determine co-disposal ratios and to predict when leachate will first be generated is hence inappropriate.

f. Knox (1991) noted that there were few examples of reported storage or S values for waste. He reported a number of unpublished attempts to appoint S values. In an experiment where waste packed in drums was saturated and then allowed to drain, S values of between 17 % and 40% were obtained. Comparing measured leachate production volumes with rainfall yielded an estimate of 10% while pumping tests at the Piesta site, Essex yielded values of between 3 and 5 %. At the Fresh Kills landfill, actual waste moisture content was in fact found to vary between 10 and 75 % (Suflita et al., 1992).

Other attempts to obtain estimates of storage were presented by Novella and Ross (1992) and Oweis et al. (1990). The use of lysimeters to obtain this data is apparently common. The validity of using pumping tests to estimate S of the waste pile is however questionable because of:

- the short duration of the tests,
- the difficulty in attaining a sustainable yield,
- pumping tests apply to saturated conditions, and
- the main assumptions of pumping test theory not being met.

It can also be expected that non saturated conditions prevail in the waste pile. Stone (1993) describes some of the issues and shortfalls of vadose zone hydrology which need to be considered.

Blight et al. (1992) found that the overall average storage capacity of a landfill is not a useful concept as it is very difficult to predict. It depends a great deal on the properties and disposition of the intermediate cover layers. The emission of leachate from a landfill may be greatly affected by either the channelling or sealing effect of intermediate cover layers.

g. The problems associated with quantifying hydraulic conductivity are similar to those of quantifying storage. Further, the concept of preferential flow paths is of importance in this regard.

#### 2.3.9.4. Preferential flow

The classical WSWB method assumes one-dimensional flow. The literature provides evidence to suggest that this is an over-simplification. Preferential flow (also referred to as channelling and short-circuiting) has been identified as an important flow mechanism (Stone, 1993; Blight, 1992, Blight et al., 1992; Lisk, 1991; Ham, 1988; Hojem, 1988; Watson-Craik, 1987; Shimell, 1986). Flow can be either vertical or lateral (Schroeder and Peyton, 1987) and a three-dimensional perspective is required. Blight (1992) found that the assumption of one-dimensional downward flow was in fact incorrect. Based on the results of her work, she suggested that most water balance methods have severe short-comings as they only consider vertical movement. Lateral flow, which can be significant, results from waste heterogeneity and layering within the waste pile.

Preferential flow results principally from the heterogeneous nature of the waste and the associated change in hydraulic conductivity. Water will follow a path of least resistance. The concept has also been used to account for the fact that leachate flow is recorded before field capacity is reached.

Heterogeneity and the existence of preferred flow paths results in difficulties in the determination of realistic and representative estimates of the fluid transmitting characteristics (Sections 2.3.3 and 2.3.4.). Knox (1991) noted that a number of workers have found relatively large discrepancies between field-determined K and laboratory-determined K and that it is now generally recognised that laboratory estimates are unreliable. Possible causes of this include:

a. the use of unrealistically high hydraulic gradients
b. disturbing the sample and re-compaction in the laboratory
c. measuring small parts of a heterogeneous whole

Conventional pumping tests have performed poorly as the assumptions related to pumping tests do not apply and sustainable yields are difficult to achieve. Knox (1991) listed the results of several attempts to achieve K information using conventional methods. Pumping rates varied between 0.1 and 2.7 L/s while K varied between 0.08 and 60 m/d. A K value of 0.008 m/d was proposed upon which leachate collection systems can be designed. In comparison Hojem (1988), using infiltrometer techniques, found K to range between 0.0006 and 13 m/d with 3 m/d being the average.

#### 2.3.9.5. Temporal changes

An aspect of moisture storage that needs to be considered and which is probably unique to the waste management field is that of how properties change with time. It is well documented in the literature that storage properties decrease with time. For example, Blight et al. (1990) report field capacity values of about 80 % for fresh waste and about 65 % for waste older than 4 years. The explanations for such phenomena include:

a. decomposition of waste with time
b. settlement induced by the weight of the waste pile
c. induced preferential flow paths (eg. settlement, desiccation cracking)
d. effective compaction of the waste
e. improvement in waste management practices over time

By using theoretical examples, Knox (1991) showed that a small change in storage caused by settlement could result in a significant change in leachate levels. Settlements of up to 50 % have been reported (Jaros, 1991 - referred to by Stone, 1993).

The difficulties associated with quantifying hydraulic parameters and the changing nature of these parameters over time certainly add to the problems of applying the WSWB method. As a result, over-simplification of the extremely complex environment tends to occur. This results in erroneous computations.

## 2.4. Methods of Calculation

### 2.4.1. The Classical Approach

Many different methods of calculation have been developed for determining leachate generation. These range from the use of the basic WSWB equation using annual average data to sophisticated computer models requiring event specific data. All, however, are based on the approach of balancing water inputs with water outputs and change in storage.

$$L = (P + W_m + B) - (R + E + G) \pm \Delta S$$

*where:*

| | | |
|---|---|---|
| $L$ | = | *leachate generation* |
| $P$ | = | *precipitation* |
| $W_m$ | = | *initial moisture content of the waste* |
| $B$ | = | *chemical and biological water production* |
| $R$ | = | *run-off* |
| $E$ | = | *evapotranspiration* |
| $G$ | = | *vapour loss in gas* |
| $\Delta S$ | = | *change in storage* |

The degree of detail included in the application of the classical WSWB method depends on the type of data available and the climatological data to be used. Problems with data availability and measurement have been discussed above. It is common practice, if data are not available, to assume data values or extrapolate data from other studies. This in itself allows for major errors. Because of the laborious nature of performing calculations using detailed climatic data, balances based on annual, seasonal or, at best, monthly time steps are preferred. Hojem (1988) investigated this aspect further and found that the results of water balance calculations using weekly data were approximately 70 % of those calculated using daily data.

### 2.4.2. Computer-based Methods

Computer models have the advantage that large data sets can be managed and tedious, repetitive work is avoided. The computer models described below were not applied or tested during this study. Rather, reliance was placed on published findings concerning the structure, usage and applicability of the models. Some of the models more commonly discussed in the literature included:

| | |
|---|---|
| EPA 1975 | (Fenn et al., 1975) |
| CREAMS | Chemicals, Run-off and Erosion from Agricultural Management Systems (Knisel 1980) |
| HSSWDS | Hydrological Simulation on Solid Waste Disposal Sites (Perrier and Gibson, 1980) |
| HELP | Hydrological Evaluation of Landfill Performance (Schroeder et al., 1984) |
| RSM | Rainfall Simulator Model (Gee; 1981,1983,1986) |

Some in-house models have also been developed in the U.K. but are not widely available. Knox (1991) argues that none have been extensively calibrated against data from full-scale waste disposal sites. He blames this on a lack of adequate field data, little pressure to demonstrate the accuracy of the models and a general lack of interest in the retrospective evaluation of the models.

The EPA 1975 model has been superseded by HELP but its simplistic nature made it popular. The method uses monthly input data to compute percolation and run-off. User defined run-off coefficients and evaporation losses (calculated using the Thornthwaite method) are subtracted from actual precipitation. The residual is assumed to form leachate. Booth and Vagt (1990) found the arbitrary assignment of parameters makes its site specific application uncertain.

CREAMS has not been widely used on landfills but formed the front runner of HSSWDS and HELP. Run-off is estimated using SCS curves and evaporation losses computed with the Penman method. The model can be run on daily data or using storm rainfall. The method requires information on antecedent conditions and can accommodate up to 7 soil layers. CREAMS can simulate observed trends but does not account for non saturated flow.

HSSWDS uses the same hydrological components as CREAMS and hence suffers from the same limitations. Neither method attempts to model the processes inside the landfill. A three year study by Gibson and Malone (as quoted by Knox, 1991) showed that HSSWDS underestimated leachate production by 10 % while manual methods yielded values 20 % less than measured volumes.

A PC-based HELP version became available in 1988. The method is regarded as the most comprehensive model available to date as it represents a realistic physical simulation of landfills owing to the number of parameters which are considered. The system can model multi-layered systems. Evapotranspiration is modelled using a modified Penman formula and surface run-off is calculated from SCS run-off curves. Percolation through barrier layers is computed using Darcy's Law and saturated K data. Some allowance is made for absorptive capacity with the user specifying initial moisture content and field capacity. In the model, apportionment of infiltrating water after evapotranspiration, into vertical percolation through the barrier layer, and horizontal runoff over the barrier layer are estimated. The model assumes no downward percolation until SMD is satisfied. Daily data are used. The applicability and accuracy of HELP is widely discussed in the literature. Some of the aspects and concerns addressed in the literature are presented below:

- Peyton and Schroeder (1988) noted that additional data are required to rigorously test many of the model assumptions and mechanism rigorously. They recognised that the lack of reliable actual evapotranspiration was a major short-coming.
- As a result of its comprehensive nature, large amounts of input data are required. Bagchi (1990) noted that the input values of the variables required by the model are based on judgement. He argued that this makes the validity of the prediction questionable. Blight (1992) and Hojem (1988), for example, had to use a combination of HELP-defined data values, estimations obtained from the literature, data extrapolated from other areas or situations and site specific measured data.
- Krantz and Bailey (1990) calibrated the model against 5 years worth of data measured at a Wisconsin site. After approximately 20 runs, the predicted volume was within

10% of the measured volume. The study did show that HELP was sensitive to the assumptions regarding absorptive capacity and initial and final moisture content of the waste.

- Booth and Vagt (1990) found that the method was not sensitive to vegetation quality and changes but susceptible to the design of the covering cap.
- Knox (1991) observed that HELP still had several disadvantages for use in the UK:
  a. it has still been subject to very few detailed calibration studies, none of which have been done in the UK,
  b. it is not particularly user-friendly
  c. it uses imperial units rather than metric, and
  d. it does not incorporate the ability to model uncertainty easily.
- Blight (1992) found that HELP had modest data requirements and was easy to run. She, however, found that its main short-coming was that it did not consider lateral flow.
- Stone (1993) stated that the model does not allow for a deterioration in the design performance of the cap.

The RSM model is empirical but a regression coefficient has to be determined for each of the four input variables. Even though some reasonable estimates were obtained by its developer, its widespread application is limited. Bagchi (1990) found that the method could be used to predict percolation through a landfill cover fairly accurately.

From his evaluation of available models, Knox (1991) found that 1975 EPA and HSSWDSA methods consistently over-estimated leachate production while HELP and RSM predictions were much closer to actual values on an average basis. However, the models are incomplete in that fundamental processes are omitted entirely or dealt with in too empirical a fashion. Further, several of the known calibration studies which produced good results were based upon simple systems such as lysimeters or sample test cells. Only the HELP model appears to incorporate all of the important components of a landfill water balance. The lack of calibration was seen as a serious drawback. Knox (1991) stated that the HELP model needs to be calibrated outside of the USA before it can be widely used. Such calibrations must be done against real site data. From this, it is questionable whether the HELP model is valid or should be applied in South Africa without proper verification.

Bagchi (1990) noted that as the computer models are based on a water balance approach, they share the inaccuracies of the method. He also argued (p. 34) that "*prediction based on models that use evapotranspiration data become more of a theoretical exercise than of any practical use, at least for the first few years after closure.*" He proposed that infiltration rates assuming between 20 and 30 % of mean annual rainfall could be a good rough indication of leachate generation. However, should the use of water balances be required by legislation, long-term climatic records of between 20 and 30 years should be used in the estimations.

Bagchi's observation that leachate generation could be estimated by assuming a percentage of MAP correlated with findings of Ham (1988) and Ehrig (1984). Ham noted that typical leachate generation results in humid areas such as central and northern Europe are 40 % of precipitation. For drier areas such as north-central U.S., a figure of 20 % is common. Ehrig expressed a range of between 5 and 35 % MAP with 15 % being typical. Unfortunately only Ham considered the type of climate. Such an approach is commonly employed in groundwater recharge estimations (Section 3).

### 2.4.3. Climatic Water Balance

The CWB only considers, in a gross fashion, the major water input component and the major moisture loss component of the balance. The use of the equation

$$B = R - E$$

is not commonly applied in the rest of the world, with only Anderson et al. (1993) and Knox (1991) presenting similar expressions. Knox used the equation to determine effective rainfall (Section 2.3.7.2.). but recorded that it was extremely difficult to determine E with any accuracy or confidence.

*The CWB method does not attempt to quantify the volume of leachate which would be generated by a waste site.* ***Rather it is a tool aimed at providing a basis on which to make a decision regarding the need for leachate management.*** The inherent climatic differences which characterise any existing or proposed waste disposal site are used for this function. Such a tool is required to properly design waste sites and promote sound site management practice. In order to be effective for these purposes, it is essential that the tool be simple, conservative and easy-to-use (DWAF, 1994a).

DWAF (1994a) propose that the CWB method is conservative in nature in that:

a. run-off is not included in the calculation and hence it is assumed that all precipitation enters the waste pile.
b. the moisture storage capacity of the waste body is not included and, as such, the ability of the waste to store water is not taken into account.

Further, it would appear that the CWB is only applicable if the waste facility is designed, constructed and operated in accordance with modern sanitary landfill practices eg. daily cover, effective capping. It is now well recognised that site management can be extremely effective in reducing the rate of leachate generation (Section 2.5.1.).

Even though the CWB method should stand on its own as it is a management decision-making tool as opposed to a means of predicting leachate generation, it suffers, at this stage, from a number of drawbacks. The method is based an a water balance approach and, as such, suffers from similar shortcomings and limitations (Section 2.7). The underlying assumptions associated with the method have not been clearly identified and described in the literature and are not readily apparent. Even though the application of the WSWB method was considered in detail by Blight (1992) and Hojem (1988), the behaviour of moisture in the waste profile was investigated (Ball and Blight, 1986) and test plot scale experiments performed (Blight et al., 1992), it is, however, questioned whether this research carried out at two locations in South Africa is sufficient to certify the validity of the climatic water balance.

## 2.5. Aspects Not Addressed Directly in the WSWB Method

Three important facets have been identified which need to be considered in the WSWB method. Even though discussed in the literature, they do not form part of the method. The three aspects are:

a. site design and management
b. dynamics of arid zone hydrology
c. changes over time

### 2.5.1. Site Design and Management

It must be recognised that the classical WSWB method *per se* does not include the positive impact of landfill management. It is argued that well managed sites will produce far less leachate than poorly managed sites. Anderson et al. (1993), Mattravers and Robinson (1991), Robinson and Grantham (1988) and Ball et al. (1987) all noted that site design and management have a significant impact on leachate generation with good management resulting in reduced generation rates. Hojem (1988, p. 118) stated that "*a poorly run landfill in a water deficit area can produce more leachate than a well run site in a water surplus area.*" Many existing sites in South Africa have not been formally sited, designed nor managed in order to achieve leachate minimisation. Thus they do not meet current standards and requirements. Older sites must therefore be considered to have the potential to generate greater quantities of leachate at a quicker rate than modern sanitary landfills.

Reitzel et al. (1991) noted that some factors impacting on leachate generation are controllable (eg. refuse density, cell depth, moisture infiltration, slope) while others are not (total rainfall, temperature and refuse composition). Site management aims to control those factors in such a way that impacts are reduced. For example, proper site design and management aims to promote run-off and reduce infiltration. Some coefficient, based on the management standard of the site, could thus be used in the WSWB to correct the P, I and R components.

Stone (1993) warned that the volume of leachate generated by a particular waste will probably remain constant through time but the rate of generation can be manipulated. He stated that the issue of leachate generation from municipal landfills is regarded as one of "*when* rather than *if*." The traditional "dry-tomb" approach to the disposal of municipal solid waste has been extensively reviewed by Lee and Jones (1991) and was seen by them as only an intermediate solution. The use of engineered caps and liners can be very effective in reducing and delaying the contaminant risk. The critical factor in determining the safe condition is the time factor. As long as the waste is there, it poses a threat.

### 2.5.2. Dynamics of Arid Zone Hydrology

It is argued by Blight (1992) that the dynamics of the waste system need to be considered. To do this, she noted that the use of daily rainfall data is more realistic than average values. There is sufficient evidence in the literature to show that leachate generation is not continuous but rather related to precipitation events (Anderson et al., 1993; Robinson and Grantham, 1988; Collins and Spillmann, 1982). Some debate exists, however, concerning the time scales of relevance.

DWAF (1994a) discussed leachate generation in terms of *significant leachate generation* which is seasonal or continuous throughout the year and *sporadic leachate generation* which results from abnormal circumstances such as excessively wet periods. They noted, that from a management point of view, significant leachate generation is of greater importance. They are supported by Robinson and Grantham (1988) who found that leachate generation rates fluctuated widely in the UK. They recorded fluctuations of more than an order of magnitude during the wetter winter period and generation approaching zero in the summer months.

However, Aguilar and Aldon (1991 - as quoted by Stone, 1993) noted that leaching and translocation of waste contaminants to groundwater is not very likely in semi-arid and arid regions under normal circumstances. Unusually severe precipitation events result in saturated flow and contaminant migration, especially if the precipitation event is of long duration and low intensity. In this particular case, mean annual precipitation was 300 mm (12 inches). It is for this reason that Lee and Jones (as quoted by Stone, 1993) stated that **it is technically invalid to suggest that because the regional net water balance is negative, no leachate will be generated.**

Collins and Spillmann (1982) noted that leachate outflow reacts immediately after heavy precipitation. From their test plot experiments in arid areas, Anderson et al. (1993) found that almost all soil moisture occurred in late winter and early spring as a result of the combined inputs of melting snow and early spring precipitation. They also found that antecedent moisture conditions varied considerably throughout the year.

It is a characteristic of arid and semi-arid climates that precipitation often occurs as extreme events (Lerner et al., 1990). Further, Blight et al. (1992) stated that even in semi-arid climates, landfills contain sufficient moisture to sustain uninhibited bacteriological activity. During "normal" or dry periods, biodegradation of the waste continues, albeit at a relatively slow rate. During extreme precipitation events, a positive water balance will exist which provides the dynamics for leachate generation and solute transport. The quality and quantity of leachate generated would be controlled largely by:

a. the duration between extreme events
b. the rainfall volume, intensity and duration of the event
c. antecedent moisture conditions
d. type of waste

The lag time between leachate being generated and reaching the base of the site may be significant. If the one-dimensional flow model were considered, the lag could be substantial and be measured in weeks or months. The three-dimensional model, including preferential flow paths, would account for rapid migration which could be measured in hours or days.

The frequency of occurrence, or return period, of these extreme events which result in leachate formation in arid areas is not discussed in the literature. However, if groundwater recharge events in similar climes can be considered, then the case of Beaufort West can be used for illustration. Seward (1988) found that the "average" interval between recharge events is 4.3 years. It is quite conceivable that similar intervals occur in the case of leachate generation at waste facilities located in arid zones.

If this dynamic of leachate generation were not considered, the WSWB method would not predict leachate formation. Detailed climatic and waste moisture information have to be used if accurate results are to be produced. From the literature, it would appear that event, daily or, at worst, weekly data would be required (Blight, 1992; Knox, 1991; Hojem, 1988; Schroeder and Peyton, 1987).

### 2.5.3. Changes over Time

An aspect that could prove to be an important source of error in the WSWB method is time or age of the site. This topic was previously addressed in Section 2.3.9.5. but warrants further evaluation. The following long-term changes with time which could impact on the rate of leachate generation have been recognised:

a. waste site management practices change over time
b. deterioration of landfill caps
c. preferential flow either induced or reduced by settlement
d. reduced field capacities
e. reduced storage capacities

In addition, Blight (1992) noted that, theoretically, a stage is reached when a landfill will no longer emit pollution in concentrations which are harmful. It is, however, estimated that it will take centuries to reach this stage.

Mattraver and Robinson (1991, p. 889) stated that "many workers undertake water balance calculations, but few of these are ever assessed afterwards, and it is even rarer for anyone to actually measure water which infiltrates through actual landfill surfaces, at various gradients and with various capping thicknesses and materials." It is possible that, with regard to changes over time, it is not the method that is at fault, but rather the user of the method. Users of the WSWB approach need to be made aware of this aspect.

## 2.6. Case Studies

The following case studies are presented so that some of the trends and work being done in the field of leachate generation are highlighted.

Collins and Spillmann (1982) used lysimeters to show that leachate was generated even when evapotranspiration was higher than precipitation. They ascribed this phenomenon to actual evaporation being less than potential evaporation. They noted that it was "*impossible to calculate the actual evapotranspiration since those factors which heavily affect the Et are unknown.*" They used an accumulated climatological water balance to demonstrate that possible seepage water could be reduced by using potential evapotranspiration.

Saxton (1983) argued that at waste sites which received less than 400 mm per annum, almost all precipitation is evapotranspired.

Keenan (1986) contended that leachate will eventually be produced at waste sites which receive more than 750 mm of rainfall per annum while those in arid areas which receive less than 325 mm are unlikely to produce leachate.

Shimell (1986) recorded that previous mistakes in quantitative assessment of leachate generation in Britain were based on inadequate information - particularly on surface run-off mechanisms, evapotranspiration and the absorption capacities of municipal solid wastes.

Korfiatis and Demetracopoulos (1986) found that most workers assume a steady-state leachate input and no leakage through the bottom liner.

Weimer (1987 - as quoted by Hojem, 1988) presented the case of two stations located 20 km apart near Hessen in Germany. Because of topography the one station receives 1 100 mm of rainfall per annum of which 55 % became leachate. The second station only receives 550 mm of rainfall per annum of which 6 % became leachate.

Peyton and Schroeder (1988) tested the HELP model against measured data from a number of small test plots and cells. They were able to get good correlations between the measured and predicted leachate volumes. They found that data availability from waste sites was a major limitation. They attributed this to waste site operators being reluctant to subject their facilities to public scrutiny and to the costs of data collection. As a result accurate data was limited and default values had to be assumed and used. When attempting to calibrate run-off numbered curves they found that at 5 sites the run-off was over predicted by an average of 30 % and under predicted at 6 sites by 21 %. They did not have reliable evapotranspiration data available to them and thus had to use a surrogate variable. They concluded that no model could be expected to reproduce any single field result because of the great variability that occurs in the field sites among identically constructed cells.

In applying the water balance method to test cell data and during field verification, Bagchi (1990) found the margin of error to be very high. Wigh and Brunner (quoted by Bagchi, 1990) reported differences of 43 % between the leachate volume predicted using average climatic data and the actual leachate produced.

Bagchi (1990) quoted work done by SCS engineers in 1976. 25 different methods of predicting leachate generation were applied at 5 sites with known leachate generation rates. The average error ranged between 83 and 1543 % with 71 % of the methods yielding over-estimates. Peyton and Schroeder (1988) estimated the error range for the HELP model to be between -96 and +449 %.

Booth and Vagt (1990) applied three different water balance methods at a waste site which was thought to be a model site until groundwater contamination was detected. The EPA Method, the HELP method and a leachate level method described by Hughes et al. (1971, 1976) were applied. The last method relates leachate generation to actual measured leachate levels, area and porosity. The method is similar to the Groundwater Level Fluctuation and Saturated Volume Fluctuation Method described in Chapter 3. In measuring the leachate levels, they recorded some anomalous rises which they ascribed to lagged or summer-storm infiltration. Booth and Vagt related the calculated leachate volumes to % MAP and obtained 23 %, 16 % and 18 % for each method respectively. The MAP was approximately 950 mm. They noted that the three methods yielded estimates of a similar order of magnitude.

Nyhan et al. (1990) found from their plot experimental work in Los Alamos that leachate was only produced after winter snow and rains. They found however, that leachate production could be reduced by changing the design of the cover. They also found that most of the leachate production could be attributed to a record snow-melt season.

Howard and M[c]Gee (1991) noted the complexity of calculating a water balance. In order to estimate the volume of leachate generated at 38 operational waste sites in the Umgeni catchment, they followed the guidelines presented by Ham (1988) in which it is assumed that 40 % of rainfall falling onto landfills will result in the formation of leachate. The validity of Ham's approximation was not addressed.

The installation of 1,2 m diameter auger holes in the waste pile of three waste sites in South Africa is well documented (Blight, 1992; Blight et al., 1992, 1990; Hojem, 1988; Ball and Blight, 1986; Ball, 1984). The three sites were the Linbro Park and Waterval sites in Johannesburg and the Coastal Park site in Cape Town. The aim of the work was to investigate the moisture and chemical profile in a waste pile. Some of the conclusions reached from this work which could be relevant to the evaluation of the WSWB method include:

- leachate was detected even though the moisture content was less than the estimated field capacity (Blight, 1992; Hojem, 1988)
- the concept of the landfill profile starting to drain only once field capacity has been reached, appears to be false (Blight, 1992).
- the waste pile shows widely varying characteristics (Hojem, 1988).
- 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 in the fill (Hojem, 1988). There is however no conclusive evidence as to where the water is going .
- Hojem (1988) showed that little downward percolation of water at Linbro Park occurred and that moisture movement is seasonal.
- the figures at the end of the dry season 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" (Hojem, 1988, p. 114).
- "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" (Hojem, 1988, p. 116).
- one-dimensional flow in the landfill is not dominant, lateral flow was found to be important.
- the moisture profile shows a very low moisture content in the upper 0,5 m of cover as well as a tendency to decrease with depth in the upper 2 m thick cell of refuse - Ball and Blight (1986) propose that these observations are indicative of seasonal upward flow of moisture under an evaporative gradient after earlier seasonal wetting.
- by reading the dates of newspapers sampled in the hole, the waste was found to be 8

years old.

It is a pity that only two or three sampling runs were performed on these holes. It is difficult to draw conclusions from such limited monitored data. The representativeness of the findings following the exposure of the waste needs to be looked at closely. However, this research provided valuable direct access to the waste which is extremely rare. New information that had previously not been available was also obtained.

Blight (1992) used the HELP model at Linbro Park and found that it predicted a lower leachate production rate than Hojem (1988). She noted that the results appeared to agree with field conditions better than Hojem's predictions. Her results were also in line with results from experiments run at test plots using sprinkler infiltrometer tests. Blight (1992) found that one of the main causes of differences between her results and those of Hojem was the method of estimating evapotranspiration. She also found that one of the major short-comings of readily available predictive computer programmes appears to be their assumption of one-dimensional flow.

The work done by Suflita et al. (1992) and Rathje (1991) on the Fresh Kills Landfill in Straten Island, New York has raised many questions regarding waste disposal and the validity and effectiveness of landfill as bio-reactors. Waste that was previously thought to be readily biodegradable was in fact found to be persistent in the waste pile. They found, for example, steak and newspapers which had been buried in the waste pile for over 15 years with little biodegradation being evident. The landfill covers over 1 200 ha and it is estimated to produce 3 ML of leachate *each day.*

Suflita et al. (1992) also found that measured methane yields are typically only 1 to 50 % of that theoretically possible. The inhibition could be due to the presence of sulphate and is almost certainly due to the limitations imposed by moisture content.

A change in moisture management approach is discussed by Uehling (1993), Suflita et al. (1992), Rathje (1991) and Ham (1988). Instead of keeping waste dry or at some optimum moisture content, the waste needs to be kept saturated to promote microbiological activity. In the Fresh Kills site, significant waste degradation was only found near the base of the site which was saturated. From a waste degradation point of view this may be important. From a groundwater pollution perspective such an approach can only have dire consequences. The view of "wet waste" is, however, aimed at speeding up decomposition such that the leachate can be managed before the liners degenerate. Uehling (1993, p. 13) passes the comment that the "dry tomb" approach was developed and is advocated by the US EPA while "the alternative approach, advocated by engineers in academia, uses water to accelerate decomposition."

Stone (1993) quotes the case of the Denver-Arapahoe waste site in Denver, Colorado. The site was established in 1966 and receives an annual precipitation of approximately 325 mm. Surface and groundwater contamination was first detected in 1980. Management practices were then changed and a 1,2 m cover was emplaced to prevent further infiltration.

## 2.7. Shortcomings and Limitations of Classical WSWB

The ensuing section provides a listed summary of the important limitations in the WSWB method recognised earlier in this Chapter. These short-comings are grouped according to limitations in the development of the method, weaknesses in the method itself and defects resulting from application.

### 2.7.1. Limitations in Development

- the *verification and calibration* of methods have not been based on actual leachate generation data measured at full-scale landfills, resulting in the validity of the method not being established under real conditions.

### 2.7.2. Weaknesses in the Approach

- is based on the assumption that *field capacity* has to be reached before leachate can be generated - sufficient evidence is produced in the literature to suggest that this assumption is in fact incorrect.
- the *dynamic* of the whole process of leachate generation is not intrinsic to the procedure, particularly with regard to changing moisture conditions, changing rates of evapotranspiration losses, changing properties of the waste pile and arid zone hydrology.
- considers *bulk precipitation* and not the nature and pattern of precipitation.
- the WSWB method is based on gross *over-simplifications* of the leachate generation process.
- owing to the very nature of the material and the environment, the parameters required by the WSWB method are *difficult to quantify* with any certainty, here the heterogeneity in space and of the waste and the quantification of actual evaporation are paramount.
- consideration of *antecedent conditions* is largely lacking, particularly with regard to moisture content and evapotranspiration.
- only *one-dimensional flow* is considered - both vertical and lateral flow along preferred pathways are now recognised as important flow mechanisms in the waste pile, a three-dimensional flow model is hence required.
- the positive impacts of *site design and management* in minimizing the rate of leachate generation are excluded.
- the *sensitivity* of the models to different components varies.

### 2.7.3. Defects Resulting from Application

- it is not recognised that almost all waste sites "regularly" generate leachate and that *water surplus conditions will at some time occur.*
- continual application of the WSWB method *without monitoring and evaluating*

*performance* of the method over time - this possibly results from little pressure to demonstrate the accuracy of the models, a general lack of interest in the retrospective evaluation of the models and the inexperience of practitioners coupled to the developing nature of the science of waste management

- the approach to the *quantification of input parameters* - values are often gleaned from the literature or extrapolated from other studies without on-site verification.
- where on-site determinations are performed, these often do not sufficiently consider heterogeneities - this results in *over-simplification.*
- the *time-step of climatic data used* varies considerably - sufficient evidence exists that small-time steps need to be used as significant errors result when coarse intervals are used.
- *short-cuts* being taken - often to avoid the costs of having to collect data or to avoid laborious data management and manipulation
- a blind application of the WSWB method *without understanding the processes* involved or the limitations of the method.
- the *exclusion of elements* of the WSWB method without proper scientific quantification or as a result of data unavailability.

# 3. GROUNDWATER RECHARGE

## 3.1. Introduction

An estimation of recharge is essential in that recharge ultimately defines the volume of water that can be abstracted from an aquifer over the long-term. The determination of aquifer replenishment is, however, also the most difficult facet of groundwater resources evaluation. The recharge process includes most elements of the hydrological cycle from precipitation to baseflow (Abrams, 1987). In the development of a particular resource, it is common for a first approximation of recharge to be made using limited available data and extrapolation of experiences elsewhere. As development and exploitation proceed, it is sound aquifer management practice to continually re-evaluate recharge based on abstracted volumes, monitored water level data and climatic data (Fleisher and Eskes, 1992).

Lerner et al. (1990) defined groundwater recharge as *the downward flow of water reaching the water table, forming an addition to the groundwater reservoir.* It must be noted at the outset that a difference exists between potential recharge and actual recharge. Antecedent moisture conditions and the non-acceptance of the aquifer of recharging water are regarded as the two most important factors which impact on potential recharge waters that reach the aquifer.

The qualitative identification of groundwater recharge is simple if monitored water level data are compared with rainfall records. Kirchner et al. (1991) and Kok (1991) presented hydrographs and rainfall data which clearly show recharge patterns (Figures 4 and 5). The quantification of recharge, however, is another matter. The presentation of recharge estimation methods in Section 3.4. highlights some of the complexities and difficulties associated with this task.

Based on their experience and evaluation of the literature, Lerner et al. (1990, p. 7) noted that:

a. there is no doubt that recharge occurs to some extent in even the most arid regions, though increasing aridity will be characterised by a decreasing net downward flux and greater time variability.
b. as aridity decreases, direct recharge is likely to become less important and indirect recharge more important in terms of total recharge to an aquifer.
c. estimates of direct recharge are likely to be more reliable than those of indirect recharge.

Balek (1987) also noted that recharge occurs even in the most arid regions, but that stream flow and ponding also have to be considered ie. indirect recharge.

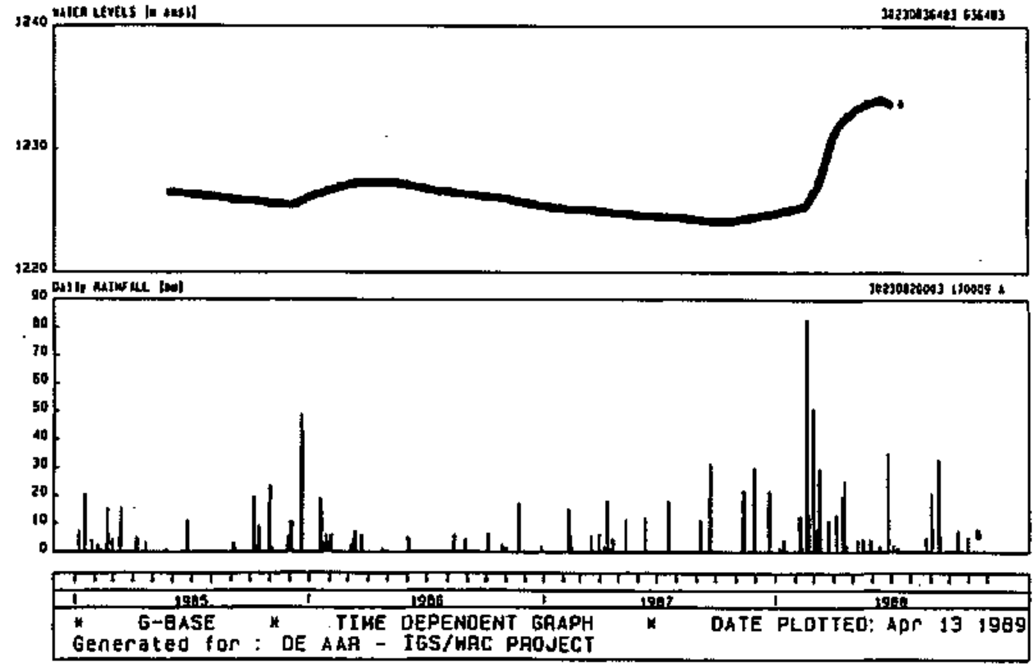



Figure 4: Water level fluctuations recorded in a borehole at De Aar.

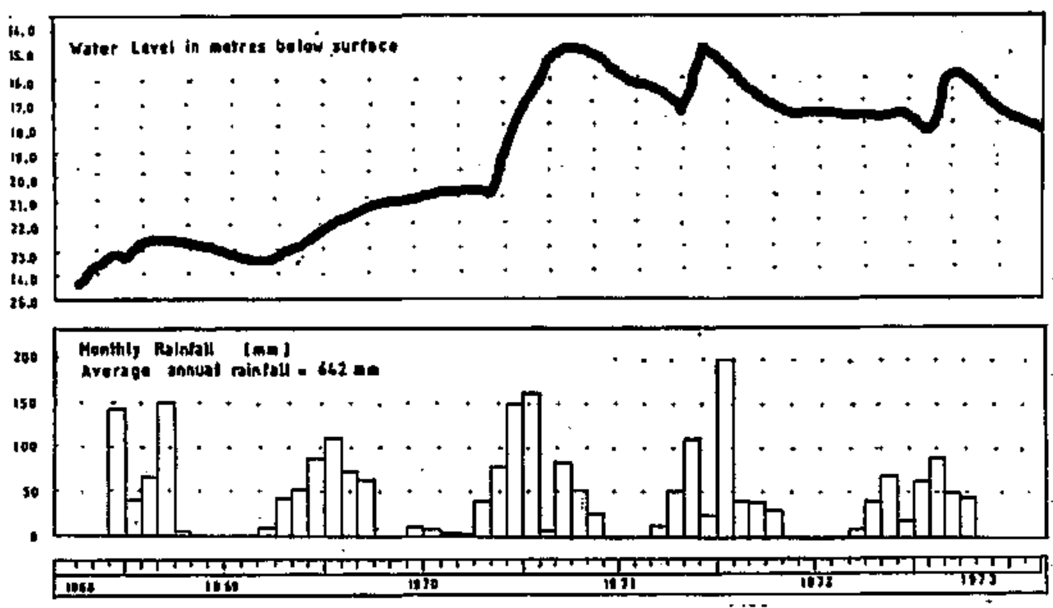



Figure 5: Water level fluctuations recorded in a borehole at Potgietersrus.

## 3.2. Generalised Theory

Groundwater recharge and techniques for the estimation thereof are described in detail by Bredenkamp et al. (1993), Gieske (1992), Lerner et al. (1990) and Simmers (1987). All four of these documents are concerned with groundwater recharge in arid or semi-arid regions. For the purpose of this study, Allison's (1987) definition of semi-arid areas being *those areas which receive less than 700 mm/a* is followed. The study of arid zone hydrology has been largely neglected in the past. In recent years it has started to receive more attention (Stone, 1993; Scanlon, 1992; Lerner et al., 1990; Simmers. 1987). This trend has been precipitated by groundwater often being the only source of water in the drier parts of the world, particularly in developing countries. Following this trend, it has been found that the *mechanisms of recharge vary considerably under different climatic conditions.* As approximately 70 % of the area of South Africa is classified as semi-arid or arid, it is appropriate that close attention be paid to semi-arid approaches. It is, however, recognised that many tools were first developed in wetter climes and have been transferred for application into the drier areas. The difference between the two thus has to be established.

Like the WSWB method, the basic axiom of recharge also conforms to the principle of conservation of mass:

$$I = O + \Delta S$$

| | | | |
|---|---|---|---|
| *where* | $I$ | = | *sum of all the inflows* |
| | $O$ | = | *sum of all the outflows* |
| | $\Delta S$ | = | *change in storage over a given time* |

In the proceeding sections, recharge will be discussed in terms of controls, time scale and mechanisms of infiltration and percolation.

## 3.3. Factors Controlling Recharge

Many of the factors controlling leachate generation also impact on recharge (Figure 6). Specifically excluded are the initial moisture content of waste, moisture resulting from the decomposition of waste and vapour losses in gas. It is not necessary to repeat the description of the factors in this section. Rather, attention will be paid to differences or particularly important aspects. Because a number of different approaches are used in estimating groundwater recharge, the description of the calculation methods also continually refers to controlling factors.

The main controlling factors of groundwater recharge are:

- precipitation and other water supplies
- geology and soil

- vegetation and land-use
- topography and landform
- groundwater condition.

All of these components have been discussed previously, either directly or indirectly. For example, topography impacts on run-off - infiltration relationships while soil is considered in cap design.

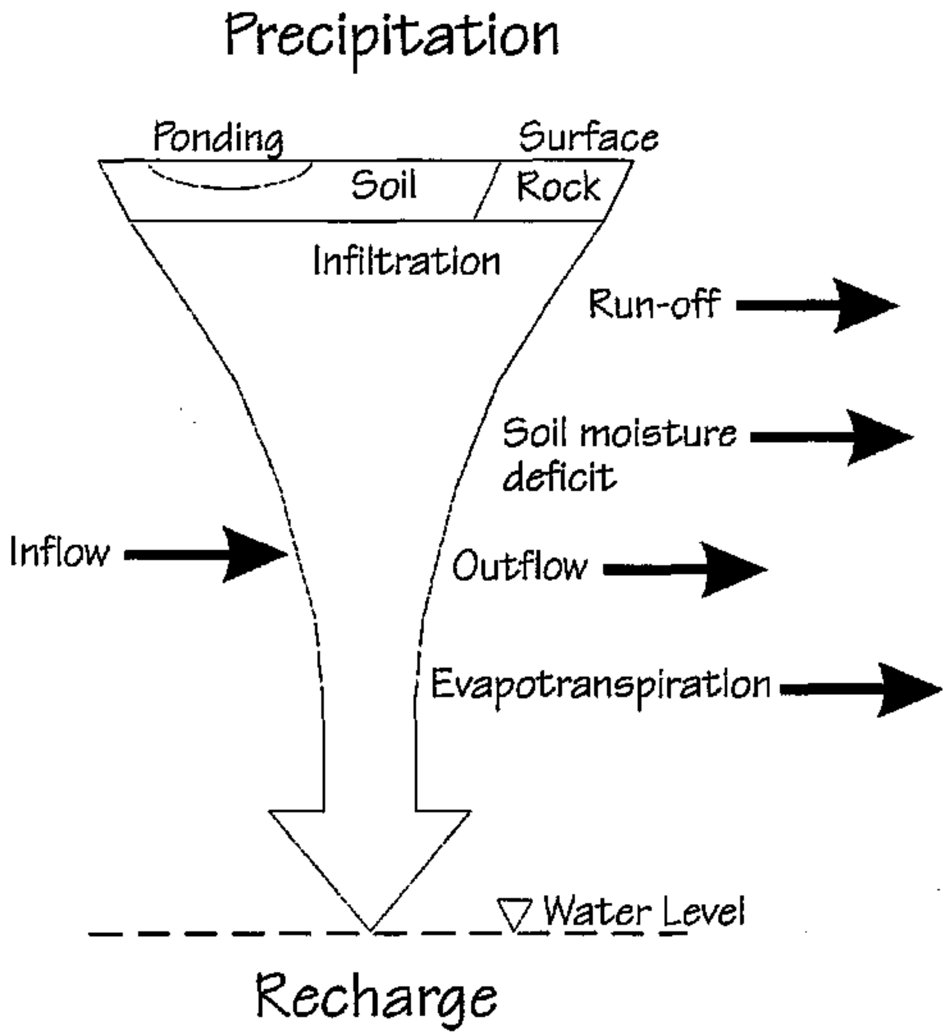



Figure 6: A schematic representation of the precipitation - recharge process.

### 3.3.1. Precipitation

In considering precipitation and time, Balek (1987) described 4 types of recharge:

a. *short-term*: this occurs occasionally after heavy rainfalls, mainly in regions without marked wet and dry seasons, antecedent moisture conditions play an important role and significant variation in recharge is characteristic.

b. *seasonal*: this occurs regularly eg. at the beginning of snow melt in temperate regions or during the wet period in wet and dry regions.

c. *perennial*: a nearly permanent downward flow exists, this usually only results from rivers and man-made structures such as dams and canals.

d. *historical*: recharge occurred a long time ago and is now contributing to present resources through some sort of *piston* mechanism. For example, water from the Great Artesian Basin in Australia was dated to be 350 000 year old.

Precipitation and the nature of precipitation are paramount in determining recharge in arid and semi-arid regions. They were considered in almost all literature in terms of magnitude, intensity, duration and spatial distribution.

A problem related to precipitation is that it is highly variable over short distances (Kirchner et al., 1991). This makes it difficult to define an "average" which would be representative of a catchment or region. Gee and Hillel (1988, p. 257) refer to this as *the fallacy of averaging*. "One approach to the assessment of groundwater in arid regions that is particularly error-prone is that of averaging of values for processes measured at specific moments and locations and the integration of such averages over space and time to characterize the entire domain. Because on average (most of the time over most of the area) the process of recharge in an arid region may be scarcely discernable one is tempted to conclude that the overall recharge in the long run is practically negligible. The problem is that most of the recharge in an arid region may be episodic (occurring in short and unpredictable events), and also may be confined to restricted portions of an area. Furthermore, seasonal rainfall patterns may be such that most of the annual rainfall occurs during winter months when evaporative demand is lowest. Such ephemeral and concentrated phenomena are usually difficult to catch in ordinary (random) sampling procedures, which in practice involve a necessarily limited number of observations."

Bredenkamp et al. (1993) argued that time lag posed an additional problem as recharge delays of up to 8 months had been reported. They proposed that one of the ways in which to circumvent the delayed response is to conform to the natural hydrological cycle which takes 12 months.

### 3.3.2. Evapotranspiration

Many of the models do not consider evapotranspiration as they only consider water entering or leaving the aquifer. Near surface processes like evapotranspiration and soil moisture deficit therefore do not have to be accounted for. It is only really the budgeting approaches which require the quantification of evapotranspiration and this component will be discussed in greater detail in Section 3.4.5.

It is recognised that evaporation accounts for some moisture loss in the recharge process. However, its quantification remains problematic. The recharge estimations entailing moisture budgeting are viewed with suspicion because of their reliance on a factor which is so difficult to quantify. As recharge is determined as a residual between various components, including evapotranspiration, the error is passed on and may be as much as an *order of magnitude* in arid environments. If it is considered that this residual is often small, then the problem of error is compounded. Williamson and Lawrence (1980) regarded *the reliance on evapotranspiration as the biggest drawback of moisture budgeting techniques.*

### 3.3.3. Water Movement

It is recognised that two main mechanisms exist for recharge from precipitation, namely direct recharge and indirect recharge. Direct recharge requires that water *infiltrate and percolate through the soil horizons and the vadose zone before it reaches the aquifer* ie. conforms to the classical model of downward percolation. Indirect recharge allows for water to *channel through the soil and vadose profile via preferred pathways.* The validity of this concept is now universally accepted, particularly in arid zone hydrology (Stone, 1993; Scanlon, 1992; Kirchner et al., 1991; Gee and Hillel, 1988; Allison, 1987, MacQueen, 1980). Lerner et al. (1990) explained that the irregular occurrence of preferred pathways in even relatively homogeneous material is an added complication for recharge estimation. The concept of preferred flowpaths is expanded on in following sections.

Lateral inflow and outflow also need to be considered in the quantification of recharge. Unlike the WSWB method, this component always needs to be included. Groundwater flow can be calculated using Darcy's Law:

$$Q = T\, i\, w$$

*where*
- $Q$ = *inflow or outflow*
- $T$ = *transmissivity*
- $i$ = *hydraulic gradient*
- $w$ = *width of section through which water flows*

With accurate data, reasonable estimates can be obtained. Owing to the problems associated with obtaining representative hydrogeological data in a heterogeneous environment (Section 3.3.5.), this component also needs to be regarded as a possible source of error.

### 3.3.4. Storage and Specific Yield

Storativity is a vital component in the assessment of aquifer recharge. The quantification of a representative storage or specific yield is also extremely difficult. This is particularly true in the fractured aquifers of South Africa. Storage is usually determined using pumping tests (Kruseman and De Ridder, 1991). The problems with applying classical pumping test techniques in fractured conditions are dealt with by Parsons (1987). The Groundwater Level Fluctuation method is particularly vulnerable to errors in S.

In trying to monitor soil moisture storage change both in time and with depth in the Karoo, Kirchner et al. (1991) had little success in tracking recharge, which was known to have occurred, using neutron probes. Gee and Hillel (1988) noted that some workers have assumed that the apparent absence of changes in moisture content at monitored depths within the vadose zone is an indication of no flow. They further state that this assumption disregards the possibility of steady flow under a gravity gradient.

Bredenkamp et al. (1993) noted that, because of the interdependence between recharge and storativity, the lack of reliable estimations of storativity is one of the reasons why recharge cannot be derived reliably and uniquely.

### 3.3.5. Geohydrological Considerations

Due consideration must be given to quantifying information required by geohydrological models. Groundwater is essentially an intangible resource and estimations have to be based on indirect determination methods. For example, the determination of the boundaries of an aquifer have to be inferred from, amongst others, geological data, topography and water level data. The determination of abstraction rates also pose problems in that the measurement of pumping regimes over time is difficult. Abstraction figures can thus usually only be considered approximations at best. In considering which is the most viable recharge estimation technique, attention must be paid to the type of data required and the accuracy of that data. Some of the main sources of error stem from:

a. heterogeneity of the geohydrological system.
b. inaccuracy of input data, ie. direct measurement data (rainfall) vs calculated data (actual evaporation).
c. difficulty in accurately measuring some parameters.
d. T and S data difficult to quantify accurately in fractured rock environments.
e. concepts of potential recharge, net recharge and actual recharge.

## 3.4. Methods of Calculation

In order to ensure that the methods used to calculate groundwater recharge can be compared with the WSWB method, this research project concentrated on recharge by rainfall infiltration or seepage. Instances and methods where recharge occurs primarily from river flow or from surface dams were excluded from this review. Owing to the large number of methods which have been developed to estimate groundwater recharge, not all can be described in this review. Bredenkamp et al.(1993), Gieske (1992), Kirchner et al. (1991), Lerner et al. (1990) and Simmers (1987) provided comprehensive descriptions of most of the available methods.

Simmers (1987) noted that *no single comprehensive estimation technique can yet be identified from the spectrum of available methods, which does not give suspect results*. Account thus has to be taken of site-specific conditions, the limitations of the methods to be used and limitations imposed by the data. Particular attention has to be paid to the reliability of the data to be used, especially when the input data cannot be measured directly.

A number of classifications of the various methods are proposed by Bredenkamp et al. (1993); Kirchner et al. (1991); Lerner et al. (1990) and Allison (1987). That of Lerner et al. (1990) is presented below:

- direct measurement
- Darcian approaches
- water balance methods (soil and groundwater)
- tracer techniques
- other, mainly empirical, methods.

Direct measurement has been performed in temperate areas with some success using lysimeters (Gee and Hillel, 1988). The expense involved and the difficulty in ensuring that the lysimeter accurately models the environment usually excludes this technique as a generally viable option. Further problems with this approach include reconstruction of natural conditions, extrapolation of point data and simulation of time. Gee and Hillel (1988) predicted that lysimeters, together with tracer techniques, offer the best hope of evaluating recharge at arid sites in the future.

Darcian approaches are also not favoured because of the current inadequacies in knowledge related to non-saturated flow. Gee and Hillel's (1988) description of the vadose zone as the *missing link* between the two branches of hydrology, namely surface and groundwater is particularly apt.

### 3.4.1. Groundwater Balance Methods

As recognised by Blight (1992) the water balance approach is also used to determine groundwater recharge. The approach is essentially the same as that followed by the WSWB method where the principle of the conservation of mass is observed. Water balance approaches estimate recharge as *a residual of all the other fluxes*. This is based on the principle that the other fluxes can be measured or estimated more easily than recharge.

It was evident from the literature that a number of different water balance equations exist. These range from detailed equations using many different parameters (Kirchner et al., 1991; Boonstra and De Ridder, 1981) to simplified equations such as those presented by Bredenkamp (1985) and Williamson and Lawrence (1980). In general terms, however, they all aim to balance inputs and outputs (inflows and outflows) against a change in volume over a specific time period.

Like the WSWB method, the parameters used depend on available data and a set of assumptions. Three methods are presented below as examples. For the sake of convenience, these methods are named after the authors who describe them.

#### 3.4.1.1. Liu and Zhang (1993) water balance method

Liu and Zhang (1993) presented the following expression of the groundwater recharge water balance method. They recognised a number of different recharge mechanisms:

$$Q = Qr + Qs + Qi + Qc + Ql$$

| | | | |
|---|---|---|---|
| *where* | *Q* | = | *the capacity of comprehensive groundwater recharge by seepage* |
| | *Qr* | = | *the capacity of rainfall seepage recharge* |
| | *Qs* | = | *the capacity of surface water seepage recharge* |
| | *Qi* | = | *the capacity of irrigation seepage recharge* |
| | *Qc* | = | *the capacity of channel losses* |
| | *Ql* | = | *the capacity of recharge by lateral phreatic flow* |

The definition of rainfall seepage recharge coefficient ($\alpha$) is:

$$\alpha = Qr / P$$

*where* *P* = *precipitation capacity*

**Note :** In a South African context, $\alpha$ is the same as % MAP which is discussed in Section 3.4.4.

Here $\alpha$ does not refer to the intrinsic infiltration parameter of the vadose zone but rather to climatic controls. Moreover, "the value of $\alpha$ varies with annual and monthly average, rainy season, dry season, and one time precipitation" (Liu and Zhang, 1993, p. 14). When calculating $\alpha$ the following three factors need to be considered:

a. "*effective precipitation capacity*" - it was thought that the annual precipitation capacity cannot completely play a role in groundwater recharge while neither can a one-time 20 minute rainfall event during the dry season. Some critical precipitation capacity (Po) has to be satisfied before rainfall can recharge an aquifer. Liu and Zhang (1993) used a Po of 10 mm per event.
b. "*influence of preceding rainfall events*" - the soil moisture content preceding the one-time event must be considered. Lithology thus has an impact on recharge potential.
c. *rainfall seepage recharge during one year as opposed to annual precipitation capacity* - this factor recognises that Po changes with time and is thus difficult to determine. The soil needs to be saturated prior to the occurrence of rainfall seepage recharge.

Liu and Zhang (1993) noted that many factors influence rainfall seepage recharge capacity, of which $\alpha$ is but one. In theory, the potential for accuracy increases when a larger number of factors are considered. But because of the inaccuracies associated with the various inputs, error in the estimation was in fact found to increase with the number of factors considered. Typical values of $\alpha$ presented by Liu and Zhang (1993) ranged between 0.13 and 0.29, depending on lithology.

#### 3.4.1.2. Bredenkamp (1985) water balance method

Bredenkamp (1985) presented the following simplified water balance equation for determining groundwater recharge:

$$Re = Abs \pm \Delta S$$

| | | | |
|---|---|---|---|
| *where* | $Re$ | = | *recharge* |
| | $Abs$ | = | *pumpage or abstraction* |
| | $\Delta S$ | = | *change in storage* |

Kirchner et al. (1991) based their study on a similar concept, but instead of Abs, they used a wider groundwater loss term which included subsurface outflow, subsurface inflow, abstraction and evapotranspiration. They noted that, except for groundwater abstraction, none of the terms can be measured directly. A drawback of the method is that it is often difficult to determine Abs and ΔS with any confidence.

### 3.4.1.3. Kirchner et al. (1991) water balance method

The method has also been referred to as the Saturated Volume Fluctuation (SVF) method. Kirchner et al. (1991) stated that the accuracy of measuring evapotranspiration is not reliable. They considered *effective* recharge as being representative of *actual* recharge less evapotranspiration.

$$I - O + Re - Q = \Delta W / \Delta t$$

| | | | |
|---|---|---|---|
| *where* | $I$ | = | *mean lateral inflow into reservoir during* $\Delta t$ |
| | $O$ | = | *mean lateral outflow out of reservoir during* $\Delta t$ |
| | $Re$ | = | *recharge of reservoir* |
| | $Q$ | = | *discharge from reservoir eg pumpage* |
| | $\Delta W$ | = | *change in groundwater volume held in reservoir* |
| | $\Delta t$ | = | *time period* |

I and O are calculated using Darcy's Law (Section 3.3.). Kirchner et al. (1991) warned that the area and period to be assessed must be carefully chosen. They recommended that at least monthly data be used for the assessment. The approach is subject to a number of possible errors but these can be minimized if the boreholes are spread over the entire domain of interest.

Even though the SVF method was developed for Karoo hydrogeological conditions, it was applied successfully to the dolomitic Grootfontein Compartment. A recharge of 12,7 % was obtained for the period January 1985 to December 1986. This estimation is the same as that determined by Bredenkamp (1985) using the GLF method, presented in Section 3.4.3.

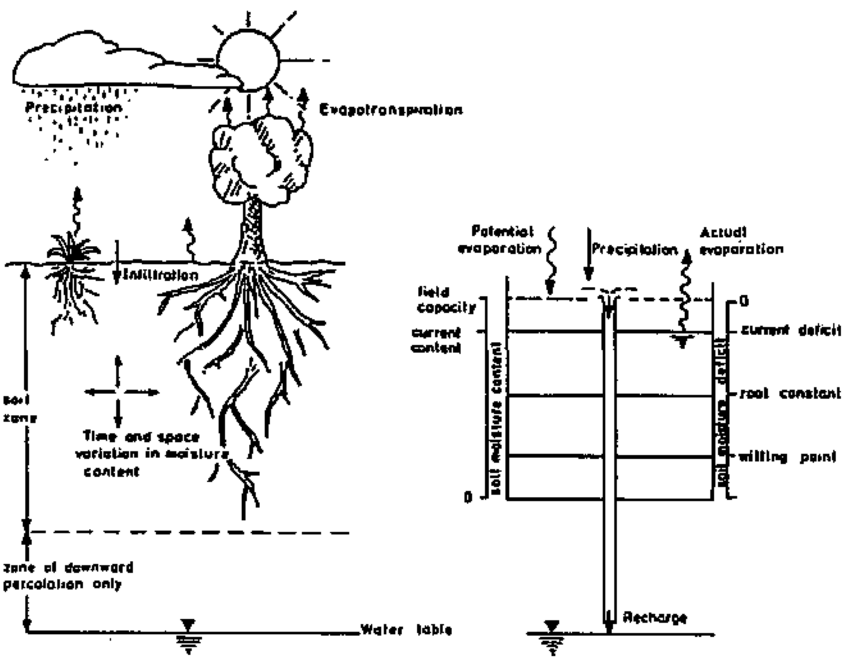
## 3.4.2. Soil Moisture Budgeting Methods

These methods are similar to those described in Sections 2.3.7. and 2.4. and include methods developed by Thornthwaite, Thornthwaite and Mather, Penman and ACRU. The methods concentrate on components in the soil horizons. The water balance methods presented in Section 3.4.1. are based on the deeper geohydrological regime. The soil moisture methods estimate the volume of water which passes through the soil horizon as opposed to estimating water which is accepted by the aquifer. The method assumes that recharge will only occur once the soil horizons are satisfied (Figure 7). It is interesting to note that Gee and Hillel (1988) refer to the Thornthwaite and Mather method as a *simplified water balance model* as recharge is calculated as the difference between precipitation, actual evapotranspiration and change in storage for any given month.

Lerner et al. (1990) said that it should be noted at the outset that:

a. such models are only simple conceptual models of the precipitation - recharge process and may not be correct for a particular situation.
b. the essence of the model is the relation between potential and actual evapotranspiration.
c. estimates are for uniform zones.

They also noted that soil moisture budgeting methods were *developed for humid climates* and have less validity in arid or semi-arid zones. These methods work best for seasonal patterns of recharge; well-developed soils which do not dry completely, when potential and actual evaporation are of a similar size, and with precipitation that is widespread and relatively uniform. Lerner et al. (1990) found that these models normally under-estimate recharge, often giving zero values.




(Lerner et al., 1990)

Figure 7: Soil moisture processes and a conceptual soil moisture budgeting procedure.

The method estimates the balance between the gains and losses of water in the soil horizons which may be expressed as:

$$Re = P - E_a - \Delta S_{soil} - R_o$$

| | | | |
|---|---|---|---|
| *where* | $Re$ | = | *recharge* |
| | $P$ | = | *precipitation* |
| | $E_a$ | = | *actual evaporation* |
| | $\Delta S_{soil}$ | = | *change in soil water storage* |
| | $R_o$ | = | *run-off* |

Should the soil water deficit be greater than the root constant, evapotranspiration will occur at a rate less than the potential rate. The root constant depends on the vegetation, the stage of plant growth and the nature of the soil. $E_a$ can be calculated using a Penman-type equation.

The ACRU model has a wide range of applications (Kienzle and Schulze, 1992; Tarboton and Schulze, 1991), including the estimation of groundwater recharge. Kirchner et al. (1991) found that the model did not consider the recharge mechanism (preferred pathway flow or macropore flow) and as a result underestimated recharge. This problem seems to be common amongst all methods based on the soil and vadose zone.

Lerner et al. (1990) made two observations which could be particularly important in the consideration of the WSWB method. The method *may* be able to be used by utilising wet season data only. This is largely in line with what DWAF (1994a) proposes. The other point of interest is that Lerner et al. (1990) confirm one of the major limitations of the WSWB method ie that the method does not describe how soil moisture moves. Upward flow and water movement in fissures, root channels and topographic depressions are ignored. Some models make use of empirical corrections to account for observation and measurement in the field. Because of a lack of measured data, this cannot be achieved by the WSWB method.

Gee and Hillel (1988) recognised that the models dealing with the vadose zone need to account for the existence and distribution of heterogeneity of soils and the location of preferred pathways. Explicit account has to be taken of unusual or extreme events and topographic features that could generate concentrated downward flows.

In their assessment of this method, Bredenkamp et al. (1993, p. 25) recorded that "the application of the soil moisture balance method, in spite of all the effort that was put into quantifying the actual evapotranspiration on a daily basis, is rather limited because of:

- the lack of sufficient daily measurement of the required data;
- the lack of a reliable way to validate the simulated recharge results."

Three different methods, which consider soil water movement in the unsaturated zone when determining recharge, yielded zero recharge when applied to Karoo environments (Kirchner et al., 1991). Yet strong evidence existed which showed that recharge had occurred. Neutron gauge measurements supported the no recharge results while groundwater levels proved that recharge had occurred. This paradox has been accounted for by the soil moisture methods not considering that recharge occurs by preferred flowpaths.

The biggest drawbacks of soil moisture budgeting techniques for determining groundwater recharge thus appear to be their reliance on evapotranspiration, their (lack of) validity in arid and semi-arid climates, the averaging of data (time steps), their lack of consideration of preferred pathways together with the assumption that soil moisture deficit has to be satisfied before recharge can occur and the lack of a reliable way in which to validate the simulation results. These limitations conform with those presented for the WSWB method in Section 2.7.

### 3.4.3. Groundwater Level Fluctuation Method (GLF)

It is easy to identify recharge episodes from borehole water level data. Thus it is appropriate that this information be used to estimate recharge. Liu and Zhang (1993) referred to this as the *Groundwater Regime Analysis Method*. The following formula is used to estimate rainfall seepage recharge over a specific time ($\Delta t$):

$$Re = \Delta h \,.\, S$$

| | | | |
|---|---|---|---|
| *where* | $Re$ | = | *recharge* |
| | $\Delta h$ | = | *change in groundwater level* |
| | $S$ | = | *specific yield* |

Liu and Zhang (1993) used the following notation:

$$Qr = \mu(\Delta) \,.\, \Delta H'$$

| | | | |
|---|---|---|---|
| *where* | $Qr$ | = | *the capacity of rainfall seepage recharge* |
| | $\mu(\Delta)$ | = | *vertical seepage recharge parameter or water-yield coefficient* |
| | $\Delta H'$ | = | *change in groundwater level caused by rainfall seepage* |

The method is attractive in that it is *easy to use* and is *based on measurable data.* S or $\mu(\Delta)$ can be determined by several methods including pumping tests, experiment or calculation. The quantification of S, particularly in fractured rock environments can, however, be problematic (Kirchner et al., 1991; Parsons, 1987). The method remains popular for areas which are heavily exploited, owing to the number of monitoring stations and the type of data available.

In this method, horizontal drainage and evaporation consumption are insignificant and can be neglected for a one-time rainfall event. Liu and Zhang (1993) noted that the method is simple, but as more long-term groundwater observation data are collected, satisfactory results can be obtained. The method is best suited to phreatic water without a large horizontal flow component.

In his use of this method, Bredenkamp (1985) stated that monthly data should be used as the rainfall recharge relationship was complex. If annual data were used, a high degree of variability in recharge estimation occurred.

One of the drawbacks of this method is defining the effective change in water level laterally. Water level changes are rarely uniform and depend on distance to nearest abstraction well and local hydrogeological conditions.

### 3.4.4. Empirical Method

Following on from the GLF method, the relationship between rainfall and recharge can be expressed by means of simple linear equations. The most basic relationship estimates that a percentage of MAP will effectively recharge an aquifer over the long-term. For many years it was assumed, for example, that 5 % MAP effectively recharged Karoo aquifers (Seward, 1988; Parsons, 1987; Vandoolaeghe, 1985; Woodford 1984). The exact origin of this figure is not known but it has formed the basis of many decisions concerning groundwater development in the Karoo. The work by Kok (1992) and Kirchner et al. (1991) has nonetheless shown this estimation to be reasonably accurate.

Gee and Hillel (1988) argued that, based on the *fallacy of averaging*, recharge estimates for arid sites reasoned on a *rule of thumb* fraction of the annual precipitation are, at best, deceptive and highly misleading and should never be used, because they consider none of the plant and soil processes that control recharge at arid sites.

A second level of formulae includes a threshold which has to be satisfied before recharge will occur. Bredenkamp (1985) proposed the following equation as a means of determining recharge:

$$Re = a\,(P - b)$$

| | | | |
|---|---|---|---|
| *where :* | *Re* | = | *recharge* |
| | *a* | = | *fraction of the effective precipitation that constitutes recharge* |
| | *P* | = | *annual precipitation* |
| | *b* | = | *threshold value below which no recharge takes place* |

Using data collected from the dolomitic aquifers at the Grootfontein compartment, *a* was set at 0.285 while *b* was defined as 310 mm. Recharge was estimated to be 12.7 % MAP during the period September 1980 to August 1983. Using larger data sets, Bredenkamp (1987) suggested that an *a* of 0.30 and a *b* of 313 were representative of dolomitic regions. This relationship was validated by Bredenkamp and Zwarts (1987) where the flow of five springs was reconstructed using the Rainfall - Recharge equation. They showed that it was possible to reconstruct spring flow records accurately using the method if consideration was given to transient groundwater storage.

Issar et al. (1985 - cited by Lerner et al., 1990) presented a similar equation determined for the central portion and coastal plains of Israel. In their equation *a* was set at 0.81 while *b* was equated to 94. Mandel and Shiftan (1981) presented a condition in their formula for Mediterranean climates. They set *a* as 0.9 and *b* at 360 when P fell between 450 and 650 mm/yr.

One of the weaknesses of empirical methods is that their derivation is often unknown. The on-going efforts in trying to establish means of accurately estimating recharge are however proving that the equations are reasonably reliable (Kok, 1992; Kirchner et al. 1991; Fleisher 1990). This approach is nonetheless used mainly for reconnaissance type studies where *margins of error are not that critical.*

### 3.4.5. Spring Discharge Method

It is contended that good long-term hydrogeological information can be obtained by analysing the response of springs to various hydrological inputs. The following equation, based on spring flow, was proposed as a means of determining average recharge from rainfall (Bredenkamp, 1985):

$$Re = Q / A$$

| | | | |
|---|---|---|---|
| *where* | *Re* | = | *recharge (mm)* |
| | *Q* | = | *average discharge of spring* |
| | *A* | = | *effective recharge area of spring* |

With this method it is assumed that all recharge will ultimately occur as spring flow. Further, abstraction volumes have to be considered for aquifers where groundwater is being withdrawn. Kok (1992) successfully used this approach to determine the average recharge of a number of cold water springs located on different lithologies throughout South Africa. By plotting the calculated recharge against annual average rainfall, he could also determine the threshold below which no groundwater recharge occurred.

### 3.4.6. Chloride Recharge Balance Method

The Cl ion is a conservative ion which is generally not lost from solution. It is soluble and not substantially taken up from solution. It is assumed that precipitation is the only source of chloride and that chloride is not lost due to subsurface chemical reactions (Fleisher, 1993). These characteristics make Cl an attractive tracer ion. The following method has been used to determine recharge:

$$Re = \frac{Cl\ rain\ (mg/L)}{Cl\ groundwater\ (mg/L)} \quad X\ 100$$

The method is rapid and easy to use but must be treated with caution because:

a. Cl concentrations in rain water are usually low and thus difficult to quantify with accuracy.
b. Cl accumulation in the soil by evapotranspiration, particularly in the drier areas, may

violate the underlying assumptions.

Kafri and Pohlandt (1985) used this method to determine a recharge of 25 % MAP for the dolomitic aquifers located of the Eikenhof area in the Klip River Basin, south of Johannesburg. Houston (1987) used this method in Victoria Province, Zimbabwe to determine a recharge potential of between 2 and 5 % MAP. Fleisher (1993) determined a recharge of 33 % MAP for the Witzand aquifer at Atlantis but warned that it could only be used in areas where leaching of Cl from the aquifer material was low and where no other sources of Cl existed. Allison (1987) noted that Cl concentrations in the atmosphere near the coast are elevated and could hence result in over-estimates of recharge.

From an evaluation of the application of this method during this review, it would appear that the Cl tracer technique yields a slightly higher estimation than those determined using other methods. The estimations are nonetheless usually within a few percent of each other.

### 3.4.7. Isotopic Methods

Isotopic methods, like the Cl method, are collectively regarded as tracer methods and are receiving more and more attention, particularly in arid environments (Eglington et al., 1993; Kirchner and Walraven, 1993; Walton et al., 1993; Verhagen, 1993). Natural isotopes such as $^{3}H$, $^{2}H$, $^{18}O$ and $^{13}C$ are commonly used in recharge studies while attention is now also being focused on other radiogenic isotopes such as $^{238}U$, $^{235}U$, $^{232}Th$ and $^{87}Rb$. The concentration and presence of isotopes are used to estimate recharge from rainfall. Little attention is paid to the processes and mechanisms of recharge. Kirchner et al. (1991) noted that these techniques have proved themselves in qualitative recharge studies but quantification remains difficult. The techniques also have the following disadvantages:

a. titrium, for example, is not conservative and can be lost from the system by evapotranspiration
b. contamination during sampling and processing is a factor which is enhanced in remote areas and at low moisture levels
c. analysis is highly specialised and costly.

### 3.4.8. Numeric modelling

The computer age has facilitated the handling of massive data sets. It is thus not surprising that numeric models are also used to determine recharge. Daily and weekly data sets are easily managed. Many of the models use variations of a detailed water balance approach. Modelling can be performed at almost any spatial and temporal time scale. The estimation of recharge using AQUAMOD is popular. The Finite Difference Model MODFLOW was used with success by Gieske (1992) in Botswana.

The ACRU model is an example of a model capable of estimating recharge (Abrams, 1987). The model is described as a multi-component physical model which is suitable for small catchment lumped modelling on catchments under 10 $km^2$. The model is based on a daily time step.

Kirchner et al. (1991) described an inverse modelling technique capable of estimating recharge. They noted that calculation of recharge to an aquifer by inverse modelling techniques must be regarded with great suspicion if the true S-values of the aquifer are not known.

The major drawbacks of using modelling techniques are:

a. specialised expertise is required for operation.
b. some models are based on matching predicted and actual observations rather than an understanding of the system and unique site-specific measured parameters.
c. operators can use the model to obtain results without fully understanding the model or the mechanisms which it tries to simulate (ie) the old adage of garbage in garbage out.
d. modelling suffers from the same weaknesses and limitations as the methods upon which they are based.

Rushton (1987) contended that perhaps the greatest advantage of a model is that it requires the investigator to identify the important mechanisms.

### 3.4.9. Other Methods

A number of other recharge estimation methods are presented in the literature (Bredenkamp et al., 1993; Gieske, 1992; Kirchner et al., 1991; Lerner et al., 1990 and Simmers, 1987). These include, amongst others, correlation analysis techniques, coefficient and experimental methods, the Zero Flux Plane method, purely Darcian flow approaches and the Soil Water Flow model. It was felt that the approaches presented above are the best recognised and most widely applied. As such, they give a good account of recharge and recharge estimation.

## 3.5. Case Studies

Watson et al. (1976) evaluated the statistical validity of applying the Maxey-Eakin method to recharge in Nevada. The method relates empirically derived % MAP to different precipitation ranges. From their work they modified the coefficients as follows:

| | |
|---|---|
| *> 490 mm/a* | *63 % MAP* |
| *381 - 490 mm/a* | *36 % MAP* |
| *305 - 381 mm/a* | *15 % MAP* |
| *8 - 12 mm/a* | *9 % MAP* |
| *< 8 mm/a* | *3.4 % MAP* |
| | |
| *Total precipitation* | *3.4% MAP* |

From this work they found that this approach did not yield accurate recharge information. The major problems with the approach was that it did not consider the geological and hydrological characteristics of the consolidated and unconsolidated rock, antecedent moisture and vegetation. They concluded that the method was sufficiently accurate as a first approximation.

Stephenson and Zuzel (1981) showed that 20 - 30 mm of rainfall over a 24 hour period was required before recharge could occur. They also found that recharge occurred infrequently and that uniform recharge from rainfall with infiltration through the zone of aeration and percolation to the water table does not usually apply in semi-arid regions.

Foster et al. (1982), working in the Kalahari sands in Botswana, stated that precipitation recharge was unlikely if rainfall was below 450 mm/a and the sand cover was greater than 4 m. Based on the work of Verhagen and Brook (1989), Gieske (1992) stated that this seemed overly pessimistic.

Bredenkamp (1987) used a number of techniques to estimate recharge in the Rietondale area. He found that recharge was influenced by the thickness and characteristics of the soil overburden. He found that the threshold value was most affected.

Edmunds et al. (1987) used solute profiling techniques in Cyprus to determine that annual recharge ranged between 10 and 94 mm/a (between 2.5 and 23 % MAP). They ascribed the variability to topography and vegetation cover. They were also able to estimate that direct recharge in Sudan amounted to 0.72 mm/a which equates to approximately 0.5 % MAP.

Knutsson (1987) compared groundwater recharge in humid and arid climates. He noted that in humid climates precipitation is greater than evapotranspiration. This results in water balance approaches being more useful in humid climates than in arid climates. Recharge in arid climates occurs intermittently and tends to be localized in the lower parts of the terrain. He further recorded that, because of differences in moisture movement, "the methods of estimation of groundwater recharge based on soil water balance or soil water flow are more important in humid areas than in arid areas."

Sharma (1987) used a number of techniques and found that recharge amounted to 15 % MAP in Western Australia. Over 50 % occurred through preferred pathways. He later confirmed this estimation using a modified Zero Flux Plane approach which excluded the need for evapotranspiration data. The method yielded recharge to be between 10 and 13 % MAP (Sharma et al., 1991).

Lerner et al. (1990) reported on hundreds of estimations of groundwater recharge in arid climates. As far as could be assessed, recharge was established in all cases. Investigations of recharge in Saudi Arabia clearly showed that groundwater recharge occurs in arid areas. Recharge was estimated to be:

a. 2.3 mm/a from a rainfall of between 50 and 100 mm/a.
b. between 7 and 10 % of MAP (130 mm/a) effectively recharged the sandstone aquifers.

Lerner et al. (1990) described recharge estimations determined for the dolomites of the Ghaap Plateau. Recharge was set at 4 % of MAP based on the spring discharge method. The Thornthwaite method was also employed using monthly data. The method predicted that no recharge occurred, "which shows that this method is not appropriate for these conditions."

Kirchner et al (1991) acknowledged that the unsaturated zone and soil type were important considerations in quantifying groundwater recharge. Using hydrograph response and time lag information, they found that most recharge occurred in areas with limited soil and where fractures and joints were exposed. They presented the following three equations for Karoo aquifers based on soil characteristics:

Re = 0.06 (P - 120) for thin soil cover
Re = 0.023 (P - 51) for thick soil cover
Re = 0.12 (P - 20) for alluvium cover

These estimates compared well with those presented by Kok (1992) and Sharma (1987) in India respectively:

Re = 0.08 (P - 100)
Re = 0.26 (P - 23)

Kirchner et al. (1991) also found that matrix flow through the soil is not considered to contribute substantially to recharge during "normal rainfall events". Major recharge only occurs after exceptional rains but above average follow-up rains in the next season are usually required to recharge the aquifers completely. They also found that, in the Karoo, *recharge occurred along preferred pathways and during major rainfall events*. This supported the statement of Sharma and Hughes (1985) that 50 % of recharge in Western Australia occurs through preferred pathways by-passing the soil profile.

Gieske (1992) found from isotopic studies that recharge takes place not only by transport through the unsaturated zone, but also by a number of other processes such as run-off percolation, direct infiltration through outcrops and river bed recharge. He estimated that recharge amounted to 23 mm/a using tracer techniques. This equates to approximately 7 % MAP.

Gieske (1992) was able to show that present day recharge was occurring in the Pitsanyane / Nnywane Basin in Botswana and that recharge and drainage were in a state of equilibrium. He compared his estimations to those obtained by other workers. Reported recharge included: between 4 and 45 mm/a in the Mokgopeetsane Catchment, between 22 and 60 mm/a in the Kanye South Wellfield with an average of about 26 mm/a being realistic and between 17 and 30 mm/a in the Grootfontein aquifer.

In the work performed by Liu and Zhang (1993), they found that depth to water table was an important factor impacting on recharge. In instances of shallow water table, a large difference existed between *actual* and *potential* recharge. In general terms, the rainfall seepage recharge coefficient increased with depth until a critical depth, after which the coefficient decreased.

Kienzle and Schulze (1992) modified the ACRU model to account for water recharging an aquifer. They determined recharge of the Lake Sibaya area to be 20.2 % MAP. This compared extremely well with earlier estimates of 21 % MAP.

Scanlon (1992) noted that preferred flow pathways are critical in considering the siting of waste disposal facilities. She employed a number of methods which determined that fissured flow was up to 350 times greater than recharge from ephemeral streams in the Nevada Desert. She estimated moisture velocity to be in the order of 10 to 70 mm/a.

Stone (1993) provides climatic data and estimates of recharge volumes in arid areas (Appendix A). These examples are clearly located in "water deficit areas" yet recharge is measurable.

Recharge estimates have received considerable attention in South Africa in recent years. Some of the results obtained are recorded below in Table 1:

Table 1: Recharge estimations for different aquifer types in South Africa.

| AQUIFER TYPE | AREA | METHOD | RECHARGE (% MAP) | SOURCE |
|---|---|---|---|---|
| Primary | Bredasdorp | spring | 5 | Kok, 1992 |
| | Cape Padrone | spring | 8 | Kok, 1992 |
| | Atlantis | Cl | 33 | Fleisher and Eskes, 1993 |
| | Atlantis | GLF | 20 | Fleisher and Eskes, 1993 |
| | Atlantis | GLF | 16 | Fleisher, 1990 |
| | Atlantis | water balance | 26 | Vandoolaeghe and Bertram, 1989 |
| | Atlantis | water balance | 25 | Vandoolaeghe and Bertram, 1989 |
| | Cape Flats | numeric model | 40 | Gerber, 1980 |
| | Cape Flats | ? | 15 - 37 | Vandoolaeghe, 1989 |
| | Cape Flats | ? | 33 | Vandoolaeghe, 1989 |
| | Yserfontein | use | 15 | Timmerman, 1985 |
| | Sandveld | use | 8 | Timmerman, 1985 |
| Karoo | Nubethesda | spring | 7 | Kok, 1992 |
| | Graaff-Reinet | use | 5 | Parsons, 1987 |
| | Graaff-Reinet | use, water balance | 2 | Woodford, 1984 |
| | Beaufort West | use, water balance | 2 | Seward, 1988 |
| | De Aar | SVF, GLF | 2 - 4 | Kirchner et al., 1991 |
| | Dewetsdorp | SVF, GLF | 2 - 4 | Kirchner et al., 1991 |
| | Bedford | spring | 6 | Kok, 1992 |
| | Somerset East | spring | 7 | Kok, 1992 |
| | Trompsburg | spring | 7 | Kok, 1992 |
| Dolomites | Verwoerdburg | water balance | 12 - 15 | Hobbs, 1988 |
| | Pretoria | spring | 13 | Bredenkamp, 1985 |
| | Pretoria | spring | 11 | Kok, 1992 |
| | Grootfontein | SVF | 13 | Kirchner et al., 1991 |
| | Grootfontein | water balance | 13 | Bredenkamp, 1985 |
| | Grootfontein | spring | 13 | Kok, 1992 |
| | Sishen | water balance | 8 | Lynch, 1984 |
| | Sishen | water balance | 6 | Bredenkamp, 1985 |
| | Klip River | water balance | 15 | Foster, 1988 |
| | Klip River | Cl | 25 | Kafri and Pohlandt, 1985 |
| | Kuruman | spring | 3 | Kok, 1992 |

*Estimations expressed as % MAP for comparative purposes*

Using natural isotopes, Verhagen (1993) was able to determine that the long-term recharge of the Jwaneng wellfield in Botswana amounted to 4 % of the 9.5 x $10^6$ $m^3/a$ groundwater abstraction (*equates to approximately 1.2 % MAP*). Verhagen also noted that periodic exceptional recharge events were the mechanism of recharge. As such, *recharge is episodic.*

## 3.6. Shortcomings and Limitations

The general shortcomings and limitations in the quantification of recharge recognised earlier in this Chapter are listed below. Where necessary, problems with particular models are highlighted.

- *direct measurement* of recharge is not possible but qualitative response is easy to prove.
- *non-saturated flow* in the vadose zone is important but knowledge is limited.
- even though the *mechanisms of recharge* have to be understood before recharge can be calculated, the mechanisms themselves are not considered by the available methods.
- the mechanisms of recharge vary considerably under different conditions, but the mechanism of *preferred pathways* is universally accepted as being important in arid zone hydrology.
- under arid and semi-arid conditions, *recharge occurs infrequently* and results from extreme precipitation events with magnitude, intensity, duration and spatial distribution being important. The collection of the data, the handling of the data and the selection of appropriate time steps are problematic.
- the *quantification of aquifer parameters* owing to heterogeneity is extremely difficult. This is particularly true when dealing with fractured aquifers. Errors associated with the quantification in time and space of S, abstraction volumes and change in water level must be considered.
- most of the methods appear to be *more suited to a first approximation* of recharge, but re-evaluation with time can lead to reasonable results being obtained.
- *soil moisture budgeting methods* used to estimate recharge face similar limitations to the WSWB method.
- *computer models* are not always seen as the answer as they require specialist expertise for operation and models suffer from the same weaknesses as the methods upon which they are based.
- the concepts of *potential recharge and actual recharge* are usually not discussed - the state of the aquifer thus needs to be considered to a greater degree.

Even with these limitations, the determination of recharge is assisted by the following positive aspects. These may be important in considering the difference in approach between leachate generation and recharge.

- recharge is known to occur, even in arid areas.
- recharge estimations are continually re-evaluated and are compared to the actual performance of an aquifer over time.
- even though no single method is available for application, recharge can be estimated

using a number of different independent techniques - this allows for comparison of results.

- some of the methods are not based on evapotranspiration.

# 4. DISCUSSION

This review has addressed the general theory of leachate generation and groundwater recharge, assessed the factors controlling the processes, presented methods of calculation, considered some case studies and identified a number of shortcomings in the two approaches. Based on the findings presented in Chapters 2 and 3, the similarities and differences between the two approaches are summarised in Table 2. The impact that these factors and considerations have on the ability of the approach to model output accurately are then summarised in Table 3.

It has been found that the two approaches share some similarities. However, a number of significant differences in the processes and methods of calculation exist which impact significantly on the ability to model output. These differences can be grouped into 5 classes:

a. validation
b. outflow as a residual
c. scale of consideration
d. depth of consideration
e. validity in arid zones.

## 4.1. Differences in the Two Approaches

### 4.1.1. Validation

#### 4.1.1.1. Observation

A major difference between the WSWB method and approaches applied to groundwater recharge lies in the validation of the predicted outcome. It has been clearly established that groundwater recharge does in fact occur in arid environments (Section 3.5.). Recharge occurrence is easily observed as a rise in the groundwater table or piezometric level (Figure 8). As recharge is the end-point of water entering the system, the total rise is an expression of the total recharge.

The proof of leachate being generated is more difficult. Indirect evidence has to be used. This can either be done by:

a. detecting groundwater contamination using groundwater quality monitoring or geophysical means, or
b. recording the volume of leachate that escapes from the base of the site.

Table 2: Summary of similarities and differences between the water balance approach and groundwater recharge approaches.

| CHARACTERISTICS | WATER BALANCE APPROACH | GROUNDWATER RECHARGE APPROACHES * |
|---|---|---|
| **SIMILARITIES** | | |
| Black box model (processes not considered) | yes | yes |
| Preferential flow paths | important process | important process |
| Easy to use, rapid methods | yes | yes |
| Over-simplified approach | yes | yes |
| Volume prediction (usually expressed as depth) | yes | yes |
| Input parameter quantification | most are difficult | some are difficult |
| Considers rainfall volume | yes | yes |
| Storage quantification | difficult | difficult |
| Considers land use / nature of surface | no | no |
| Considers changes with time | no | no |
| Prone to fallacy of averaging | yes | yes |
| Extrapolation of data if site specific data not available | yes | yes |
| Uses long time steps | yes | yes |
| Used in computer models | yes | yes |
| **DIFFERENCES** | | |
| Proof of leachate / recharge occurring | indirect | direct |
| Number of approaches and techniques | single | multiple |
| Methods verified using real data | seldom | common |
| Retrospective checking against measured field data | no | yes |
| Climate of method development and calibration | humid | humid, arid |
| Valid for arid zone hydrology | no | yes |
| Determined as a residual | yes | no |
| Determined as an end product | no | yes |
| Depth of interest | at surface | saturated zone |
| Scale (area considered) | small | large |
| Averaging over large areas | no | yes |
| Considers time lag | no | yes |
| Required interval of time data | short | long |
| Moisture inputs | rain, waste | rain |
| Considers rainfall pattern and intensity | no | not needed |
| Considers antecedent moisture conditions | no | not needed |
| Reliance on evapotranspiration | yes | no |
| Quantification of evapotranspiration | difficult | not needed |
| Based on concept of soil moisture deficit | yes | no |
| Form of outputs | lateral, vertical | vertical |

* Note: excluding soil moisture budgeting approaches

Table 2: Summary of similarities and differences between the water balance approach and groundwater recharge approaches.

| CHARACTERISTICS | WATER BALANCE APPROACH | GROUNDWATER RECHARGE APPROACHES * |
|---|---|---|
| **SIMILARITIES** | | |
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| Input parameter quantification | most are difficult | some are difficult |
| Considers rainfall volume | yes | yes |
| Storage quantification | difficult | difficult |
| Considers land use / nature of surface | no | no |
| Considers changes with time | no | no |
| Prone to fallacy of averaging | yes | yes |
| Extrapolation of data if site specific data not available | yes | yes |
| Uses long time steps | yes | yes |
| Used in computer models | yes | yes |
| **DIFFERENCES** | | |
| Proof of leachate / recharge occurring | indirect | direct |
| Number of approaches and techniques | single | multiple |
| Methods verified using real data | seldom | common |
| Retrospective checking against measured field data | no | yes |
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| Valid for arid zone hydrology | no | yes |
| Determined as a residual | yes | no |
| Determined as an end product | no | yes |
| Depth of interest | at surface | saturated zone |
| Scale (area considered) | small | large |
| Averaging over large areas | no | yes |
| Considers time lag | no | yes |
| Required interval of time data | short | long |
| Moisture inputs | rain, waste | rain |
| Considers rainfall pattern and intensity | no | not needed |
| Considers antecedent moisture conditions | no | not needed |
| Reliance on evapotranspiration | yes | no |
| Quantification of evapotranspiration | difficult | not needed |
| Based on concept of soil moisture deficit | yes | no |
| Form of outputs | lateral, vertical | vertical |

* Note: excluding soil moisture budgeting approaches

Table 3: Impact of the similarities and differences between the two approaches on the ability to model output accurately.

| FACTOR / CONSIDERATION | WATER BALANCE APPROACH | GROUNDWATER RECHARGE APPROACHES * |
|---|---|---|
| **SIMILARITIES** | | |
| Black box model (processes not considered) | **significant** | no |
| Preferential flow paths | **significant** | **minor in general, major in arid areas** |
| Easy to use, rapid methods | no | no |
| Over-simplified approach | significant | minor |
| Volume prediction (usually expressed as depth) | n/a | n/a |
| Input parameter quantification | significant | **significant** |
| Rainfall volume | no | no |
| Storage quantification | noticeable | **significant** |
| Land use / nature of surface | minor | no |
| Changes with time | minor | no |
| Fallacy of averaging | **significant** | **noticeable** |
| Extrapolation of data if site specific data not available | noticeable | noticeable |
| Long time steps | **significant** | no |
| Computer models | n/a | n/a |
| **DIFFERENCES** | | |
| Proof of leachate / recharge occurring | **significant** | *significant* |
| Number of approaches and techniques | **significant** | *significant* |
| Methods verified using real data | **significant** | *significant* |
| Retrospective checking against measured field data | **significant** | *significant* |
| Climate of method development and calibration | **significant** | *significant* |
| Valid for arid zone hydrology | **significant** | *significant* |
| Determined as a residual | **significant** | n/a |
| Determined as an end product | n/a | *significant* |
| Depth of interest | noticeable | *minor* |
| Scale (area considered) | **significant** | *minor* |
| Averaging over large areas | n/a | minor |
| Time lag | noticeable | minor |
| Required interval of time data | **significant** | *significant* |
| Moisture inputs | n/a | n/a |
| Rainfall pattern and intensity | **significant** | *significant* |
| Antecedent moisture conditions | **significant** | *significant* |
| Reliance on evapotranspiration | **significant** | *significant* |
| Quantification of evapotranspiration | **significant** | *significant* |
| Concept of soil moisture deficit | **significant** | *significant* |
| Form of outputs | **significant** | minor |

Note:
* Excluding soil moisture budgeting approaches
1 Impacts recorded in *italics* are regarded as important <u>positives</u> or <u>advantages</u> in terms of the approaches' ability to model output relatively accurately.
2 Impacts recorded in **bold** are regarded as important <u>drawbacks</u> or <u>disadvantages</u> in terms of the approaches' ability to model output relatively accurately.

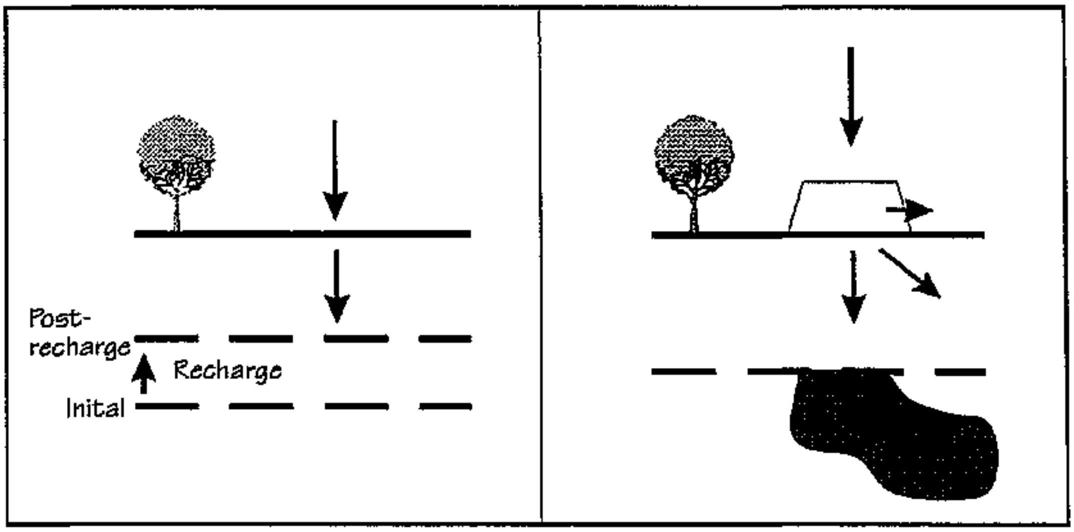


Figure 8: Output flow directions to be considered in (a)groundwater recharge estimation and (b) leachate generation estimations.

If groundwater contamination is detected, it can only *confirm* that leachate generation has occurred and that it has impacted on the groundwater regime. No estimation can be made regarding the volume of leachate generated. The literature abounds with evidence that groundwater resources have been contaminated by waste disposal activities, including cases which experience arid conditions.

The detection of leachate emanating from a waste disposal site into a groundwater body is difficult, particularly under drier conditions. Density differences between the leachate and the regional groundwater body may produce plumes within, and often at the base of, groundwater flow systems. An integrated sample from a fully penetrating screened monitoring well may also be too diluted by non-contaminated flow to be useful in detecting contamination. Further, in semi-arid climates, leachate releases are not constant. This contributes to the difficulty in detecting the plume. These situations can result in the misinterpretation of data and lead to a wrong impression being created concerning contamination. From this, it is important that the time-scale of leachate generation be regarded.

It is therefore certainly not comforting that few cases of groundwater contamination by landfill have been identified or reported in South Africa. This could be due to a number of possible reasons:

a. groundwater contamination might not in fact be a problem.

b. effective monitoring does not take place.
c. monitoring has not detected the contamination
d. the site has not been in operation for sufficient time for detectable impacts to be recorded.

The validation of the WSWB method on the grounds that contamination has not occurred is hence not reasonable. Because groundwater contamination at landfills is at present irreversible, a far more conservative approach than the WSWB method should to be adopted.

A number of questions will always remain if recording the volume of leachate exiting the base of the site is used to verify the WSWB methods. The output from a waste disposal site can occur in 3 forms (Figure 8):

a. leachate emerges at the surface, along the base of the site.
b. leachate exits the base of the site, but moves laterally for some distance in the vadose zone, and
c. leachate exits the base of the site and percolates downwards into the groundwater body.

In trying to measure the volume of leachate generated, one has to be sure that all components of leachate are monitored. Liners can assist in ensuring that the total volume of leachate is captured, but liners are known to fail and thus the accuracy of the volume measured remains in question.

#### 4.1.1.2. Number of techniques

A number of different techniques can be used to estimate recharge. Williamson and Lawrence (1980) noted that the different recharge estimation techniques can complement rather than compete against each other. If all of the techniques yield a similar result, it would suggest that the determined value is probably representative of actual conditions. This is particularly true when methods using independent parameters are employed eg. Cl method and empirical method. The tools used to estimate of leachate generation are all based on some form of water balance approach. As a result, all estimations are based on the same underlying principles, assumptions and short-comings.

#### 4.1.1.3. Retrospective checking

It is sound practice in geohydrological studies to continually re-assess estimates of groundwater recharge against measured data (Section 3.1.). This allows for improvement in the estimate as well as the validation of the technique used. Leachate generation estimations, on the other hand, are rarely checked. This could be due to the difficulty associated in obtaining reliable data, little pressure to demonstrate the accuracy of the method or a general lack of interest in retrospective assessment (Section 2.4.).

### 4.1.2. Outflow as a residual

A problem that has been identified with the water balancing approach was that output is determined as a residual ie. the output is determined by subtracting all the other components from the incoming whole. This results in the errors of all the other fluxes accumulating in the answer.

Further, the residual is often a small difference resulting from large numbers. Small errors in the components could thus result in large errors in the output estimation. Some theoretical calculations are used to explain this (Table 4). If the % change in B is compared to the resultant % change in A - B, then it is clear that a small change in the former results in a bigger change in the latter. If this aspect is considered further, the resulting compounded error would be dramatic should the 0.7 factor used in the CWB method, for example, in fact be closer to 0.6 or 0.5. The reliance of the budgeting technique on evapotranspiration, which is extremely difficult to quantify, is thus regarded as a major drawback (Williamson and Lawrence, 1980). Large errors must be expected. However, the real danger of relying on a parameter which cannot be quantified lies in the cumulative error of the budgeting approach.

Table 4: Theoretical examples depicting the compounding of errors in the use of residuals.

| A | B | % CHANGE IN B | A - B | % CHANGE IN A - B |
|---|---|---|---|---|
| 100 | 101 | **0.0** | -1 | **0** |
| 100 | 110 | **8.9** | -10 | **900** |
| 100 | 130 | **28.7** | -30 | **2900** |
| 300 | 301 | **0.0** | -1 | **0** |
| 300 | 330 | **9.6** | -30 | **2900** |
| 300 | 350 | **16.3** | -50 | **4900** |
| 600 | 1 500 | **0.0** | - 900 | **0** |
| 600 | 1 400 | **6.7** | - 800 | **11** |
| 600 | 1 200 | **20.0** | -600 | **33** |

### 4.1.3. Scale of consideration

The question of scale was found to be a key difference between the two processes. In the case of recharge estimation, larger areas measured in $km^2$ are considered. In such instances, a number of generalizations can be made while the physical environment tends toward homogeneity (Figure 9). Estimations can be made using coarse input data and a black box approach.

Leachate generation, however, is considered on a much smaller scale. The area of interest would be measured in ha (Figure 9). Because of the smaller scale, leachate generation is generally more difficult to address owing to the detail and accuracy of data required and the invalidity of generalisations. The heterogeneity of the environment has to be considered and averaging over large areas cannot be applied. The processes involved also have to be considered more closely than in the case of regional studies. It is for this reason that preferential flow, the nature of precipitation event, antecedent moisture conditions and soil moisture deficit need to be included in estimating leachate generation.

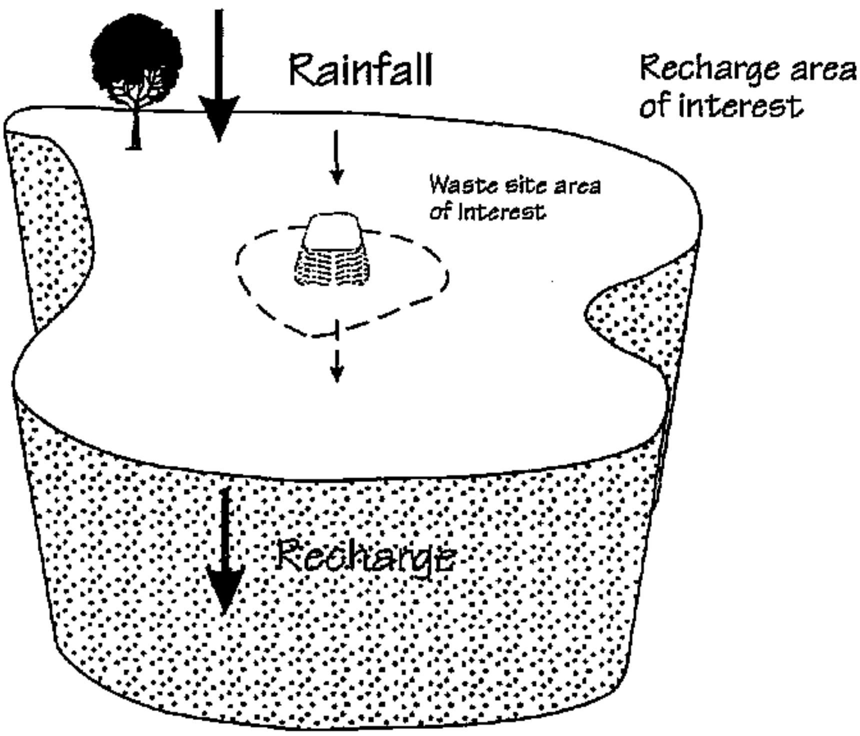


Figure 9: Scales considered in groundwater recharge and leachate generation studies.

Lerner et al. (1990) discussed the time period over which recharge is averaged. *For small study areas, arid areas and design-type investigations, instantaneous or event scales are used. For large areas, wetter climates and reconnaissance level investigations; annual, historical or even geological time is used.* Following this guide, the application of the WSWB method to waste disposal facilities in most of South Africa would have to use ***instantaneous*** or ***event-scale*** data. This is in line with the findings of Ball (1992) and Hojem (1988). As groundwater recharge usually occurs over a much larger area and a component of time lag exists, a coarser time step would be acceptable (Bredenkamp et al., 1993). Cognizance needs to be taken of the fallacy of averaging a non-linear relationship (Section 3.3.1.).

Lerner et al. (1990, p. 127) also recorded that the time-step used in soil moisture models is critical. Longer time-step, with the same parameters, lead to lower or zero recharge estimates. They noted that "all recent work recommends a daily time step for humid zones. Intervals of less than a day, eg. ones for both day and night, or storm based intervals, may be needed in arid and semi-arid areas, that is if the methods can be made to work at all."

### 4.1.4. Depth of consideration

A significant difference between the two approaches is the depth to be considered. Waste disposal sites are at surface while groundwater recharge occurs in the sub-surface (Figure 8). This results in two specific considerations:

a. evapotranspiration has to be considered in the WSWB method
b. recharge is an end product of the infiltration and percolation process.

Evapotranspiration is extremely difficult to quantify and significant errors in estimation can be expected. Further, because of the residual nature of the output estimation, the errors are passed into the final calculation. Recharge estimations do not consider evapotranspiration losses as these usually occur in the zone above the water table. The observed rise in water level occurs after evapotranspiration losses have been accounted for, and as such, evapotranspiration forms part of the black box.

### 4.1.5. Validity in arid zones

The most significant limitation of the classical water budgeting techniques is that the approach is not valid in arid or semi-arid climates. Lerner et al. (1990, p. 120) noted that "soil moisture budgeting methods were developed for humid climates and have less validity in arid or semi-arid zones. They work best for seasonal patterns of recharge, well developed soils which do not dry completely, when potential and actual evaporation are of a similar size, and with precipitation that is widespread and relatively uniform." Lerner et al. (1990) found that these models normally under-estimate recharge, often giving zero values. Gee and Hillel (1988, p. 259) concur by stating that "while simplified water balance models may be adequate for humid or temperate climate situations, they have not been tested under arid climate situations."

The WSWB method is reasonably well supported in Europe. It is possible that the method is valid in climates were rainfall is usually higher than evapotranspiration and rainfall patterns are evenly spread through a season (Gee and Hillel, 1988). The problem is that the method has been imported into semi-arid regions where moisture movement mechanisms are different from those of wetter climes. This results in the technique not being valid. The work done on ACRU could be misleading in that much of its calibration and development has been based in Natal where the climate approximates that of Europe to a certain degree.

In considering the American experiences, much of the work could have either been done in the wetter parts or those parts where snow melt is an important part of the hydrologic cycle. Stone (1993) also challenged the use of water balance approaches in arid and semi-arid areas. He reported that of 300 waste sites investigated as part of the Californian Solid Waste Assessment Test (SWAT), over 250 were found to be producing leachate. (90 % of these landfill sites receive less than 375 mm/a). The results of the SWAT contradicts the statement of Fenn et al. (1975 - as quoted by Stone, 1993) that " .. leachate problems will be virtually non-existent at sanitary landfills in arid parts of the country." The SWAT results also challenge the findings of Saxton (1983) and Keenan (1986), presented earlier in Section 2.6.

De Bruin (1987, p. 74) stated that "it can be said that in the temperate climates the limiting factor for evaporation is the available energy, whereas evaporation is limited by the available water in (semi-) arid regions." He also noted that the evaporation from the soil is generally negligibly small in the temperate regions, but can be dominant in arid areas.

A number of authors asserted that soil water balance techniques were only applicable in humid areas and not in arid areas (eg. Stone, 1993; Lerner et al., 1990; de Bruin, 1987; Knutsson, 1987). Because of this, it must be argued that the WSWB method is also not transferable to drier climates. The chief reasons for this seem to be the dynamic of the arid zone, the reliance on evapotranspiration in the estimation and the predominance of arid zone recharge occurring during extreme but infrequent events.

## 4.2. Are Recharge and Leachate Generation Estimation Methods Equatable?

The question needs to be asked whether leachate generation equates to groundwater recharge? A number of similarities have been identified, including some of the factors controlling the two processes, some of the methods of calculation and some of the limitations of the methods.

However, the fundamental differences between leachate generation and groundwater recharge (Table 2) suggest that the two do not equate. Leachate generation occurs near surface as water passes through the landfill, exiting usually at or near the base of the system (Figure 8). Precipitation is also not the only source of water in the generation of leachate as additional moisture can be derived from the incoming waste as well as from chemical and biological activity within the waste pile. Groundwater recharge, on the other hand, is essentially an end product ie. the volume of water that *can* or *does* enter the aquifer system which results in replenishment.

The fundamental differences in the two processes indicate that a direct comparison between the two is not legitimate. Further, because of the different scales involved in trying to predict output, the estimation techniques are also not interchangeable. It thus cannot be stated that one approach is more appropriate than the other.

## 4.3. The Need for Knowledge Transfer

A strong need exists for the transfer of knowledge between disciplines, especially from focused disciplines into multi-disciplinary arenas such as waste management. It has been argued in this treatise that groundwater recharge is known to occur in arid areas (Section 3.5.). Often the exact processes or driving forces behind the processes are not quantified nor well understood. The fact that water can enter the sub-surface even under unfavourable circumstances needs to be recognised.

Tools for the estimation of recharge are based on observation. As such, the use of recharge estimation tools is thus a *retrospective* type of approach based on knowledge. Leachate generation on the other hand remains essentially *predictive* in nature as verification and validation are difficult to accomplish.

The limitations associated with water balancing or budgeting techniques also needs to be more closely examined (Section 3.4.2.). By applying water balance approaches to recharge estimations, a number of serious short-comings were identified. These include:

a. the approach is based largely on evapotranspiration which is difficult to quantify.
b. recharge is determined as a residual with errors being compounded in the output estimation.
c. the assumption that SMD has to be satisfied before moisture movement can occur.
d. the assumption that leachate is generated under normal or average conditions.
e. preferred flowpaths and the dynamics of movement are not accounted for.
f. that the method is not valid for arid and semi-arid regions.

In addition, the literature revealed the following important concepts concerning arid and semi-arid zone hydrology:

a. recharge occurs infrequently with extreme events playing a far greater role in aquifer replenishment than normal or average precipitation events. As a result, a positive moisture balance will exist during these events.
b. under drier conditions, water movement along preferred flowpaths is accepted to be the major flow mechanism, as opposed to the more classical model of percolation through the soil and vadose zone profile.

All methods and approaches are based on certain assumptions. The ability of the tools to accurately simulate what occurs in the environment depends largely on the assumptions being valid (ie. approximating reality) and the quality of the data used. Both the leachate generation and groundwater recharge quantification techniques have limitations which relate to the degree of accuracy in this regard.

## 4.4. Future Actions

One of the objectives of the project was to identify the more appropriate approach (Section 1.2.). It has been found that the recharge estimation techniques are capable of providing reasonable answers, despite a number of limitations and shortcomings. It is also presented that the classical WSWB method, including HELP, is not capable of providing valid information pertaining to leachate generation in arid and semi-arid regions. Having said this, ***it does not imply that recharge methods can be used to predict leachate generation***. The processes and mechanisms guiding the two have been found to be too dissimilar to allow for a direct transfer of routine. Thus there exists a major challenge in developing a means of reliably predicting leachate generation in semi-arid climates. However, until such time that leachate generation estimation tools become available, a conservative approach to the problem needs to be taken. Appropriate siting is nonetheless seen as the only real long-term solution.

The continual use of the classical WSWB method to predict leachate generation needs to be addressed. Further, the applicability of using the CWB method (which is based on water balance principles) as a basis for the formulation of policy and legislation also needs to be considered further. South Africa can benefit from the lessons of the rest of the world. Stone (1993, p. 5) reported that "the Fenn report presented model generated data for three climatic areas. A theoretical 0 mm percolation figure was calculated for the semi-arid Los Angeles area. This *no leachate* estimation influenced opinions in the US during the late 70's and 80's about landfill design and the need for aquifer protection measures. Such view points, now known to be incorrect, have unfortunately become entrenched in some official policy." The panic and economic drain which resulted after the Love Canal saga and the widespread detection of contamination by landfill in the US are well documented elsewhere (Stone, 1993, 1992, 1991; Parsons, 1992; Lee and Jones, 1991; Odendaal, 1991). A pro-active approach to this problem is required if we are not going to follow the USA route.

Even though South Africa appears to be lagging behind the rest of the world in the debate on the estimation of leachate generation, the problem appears to be widespread. Literature from, amongst other countries, the USA, the UK, Germany and Canada are testimony to this. With respect to recharge quantification, South Africa appears to be keeping pace, if not being one of the leaders, with the rest of the arid and semi-arid world.

The myth that leachate is not generated in large parts of South Africa, created by the WSWB method, also needs to be dismissed. The waste community needs to be made fully aware of the invalidity of the method. *Its use for predicting leachate generation, for determining co-disposal ratios, setting of design and engineering requirements and in classification systems has to be halted.* Education of the broad spectrum of parties involved in waste management will be paramount in this regard. This can be achieved through presentations at seminars and workshops, publishing of articles in journals and trade magazines and the wide distribution of this report. Both the DWAF and the Institute of Waste Management could facilitate this process.

From the literature survey, it has been shown that the use of the classical water balance approach to predict leachate generation is invalid. An urgent need therefor exists for the development of a tool to predict leachate generation accurately, particularly under arid conditions. Further, this tool needs to be based on, and / or verified against, real data measured at a waste disposal site. The collection of such dedicated data will be technically difficult to collect, be time consuming to achieve and, most importantly, will probably be prohibitively expensive to do. It is further questionable whether such research would be of value. It is therefore proposed that a workshop be arranged to debate the problem and see whether it is possible to identify a practical alternative which could provide reasonable estimates. Such a workshop could be held in conjunction with the education initiatives proposed above.

## 4.5. Meeting of Research Objectives

The research objectives set out in Section 1.2. have been met by the execution of a detailed literature review and discussions held with a number of experts in the fields of waste management and geohydrology. Both international and local approaches in leachate generation (Chapter 2) and groundwater recharge (Chapter 3) were assessed. A number of similarities and differences between the two approaches were found when compared to each other (Chapter 4). It was also found that the generation of leachate and the quantification thereof is an area of deliberation both in South Africa and the rest of the world.

The identification of the more appropriate approach has, however, not been possible. Even though it is argued that recharge estimation techniques have the advantage in that they are retrospective in nature, leachate generation and recharge are distinctly different and thus cannot be equated.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1. Conclusions

- One of the major limitations in the assessment of the validity of the classical WSWB method is the lack of reasonably accurately measured leachate generation data from waste disposal sites.

- Three methods of assessing leachate generation were recognised, all of which are based on the water balancing technique. These are the classical approach, computer models and the CWB method.

- The concept that SMD has to be satisfied before leachate can be generated has been found to be invalid. Instead, the mechanism of preferential flow has to be considered.

- The quantification of the input data required by the WSWB method is difficult. This is particularly true of evapotranspiration, which is crucial to the estimation procedure. Large errors in prediction must therefor be expected.

- The validity of the classical WSWB method remains in question as the method is seldom verified or calibrated against real data measured at landfill sites. This is particularly true in arid climates.

- A major challenge in developing a means of reliably predicting leachate generation in semi-arid climates exists.

- Recharge to groundwater is relatively easy to recognise by means of rising water levels.

- A number of independent methods are available for the estimation of recharge. This allows for the comparison of results as well as the validation of the various techniques.

- Water budgeting techniques, when applied to recharge investigations in arid areas, usually predicted that no recharge would occur when, in fact, recharge had been observed. The technique has thus been found to be invalid in drier climates.

- By researching a number of case studies, it was clearly established that recharge occurs in arid zones.

- It was, however, found that under dry conditions recharge occurs infrequently and that preferential flow is an important mechanism in the process.

- In comparing the two approaches, a number of similarities were found. However, significant differences were also recognised, including the validation of the approaches, the calculation of outflow as a residual, the scale of consideration, the depth of consideration and their validity in arid zones.

- The most significant limitation of classical water budgeting techniques is that the approach is not valid for arid or semi-arid climates.

- The classical WSWB method, including HELP, is not capable of providing valid information pertaining to leachate generation in arid and semi-arid regions.

- Recharge estimation techniques are capable of providing reasonable answers in all climatic conditions, despite a number of limitations and shortcomings.

- The fundamental differences between the processes of leachate generation and recharge, and the estimation thereof, suggest that the two do not equate.

- It *cannot* be said that either the WSWB approach or groundwater recharge approaches are more appropriate.

- It also *cannot* be concluded that recharge estimation methods can be used to predict leachate generation.

- There is a definite need for the exchange of knowledge between disciplines, especially focused disciplines into multi-disciplinary arenas such as waste management.

## 5.2. Recommendations

- The continued use of the classical WSWB method to predict leachate generation, determine co-disposal (solid/liquid) ratios and define waste site design and management requirements needs to be addressed.

- The validity of HELP has not been established in South Africa. It should therefore not be applied in South Africa without proper verification.

- Until such time that reliable leachate generation estimation tools become available, a conservative approach to the problem needs to be taken.

- The limitations of the classical WSWB method need to be made known to the broader waste community. This can be achieved through workshops, seminars, publications and the wide distribution of this report. Both DWAF and the Institute of Waste Management could facilitate this process.

- It is proposed that a workshop be arranged to debate the problem of leachate generation estimation and to see whether it is possible to identify a practical tool capable of providing reasonable estimates. Such a workshop is regarded as an alternative to initiating difficult, time consuming and expensive research.

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## APPENDIX A

Report prepared by Andrew W Stone

Landfill leachate generation and groundwater contamination in arid and semiarid areas.

# LANDFILL LEACHATE GENERATION AND GROUND WATER CONTAMINATION IN ARID AND SEMIARID AREAS

A Report Prepared for the CSIR,
Division of Water Technology,
Western Cape Branch,
Stellenbosch, South Africa.

Andrew W Stone

New Hampshire, United States of America

December 1993

# LANDFILL LEACHATE GENERATION AND GROUND WATER CONTAMINATION IN ARID AND SEMIARID AREAS

**Andrew W Stone**

## 1 INTRODUCTION

This report is a synthesis of information pertaining to threats to ground water resources from landfill leachate generation in semiarid areas of the United States. The report considers hydrogeological first principles and has been prepared from a review of literature. Information sources included scientific literature and government reports, and discussions held by the author with U.S. engineers and hydrogeologists involved with ground water protection, landfill design and water quality monitoring.

## 2 BACKGROUND TO THE REPORT

The background to this report stems from a paper on the topic of aquifers and landfills presented in Johannesburg, (Stone, 1991). The paper discussed the importance of viewing landfills as an integral part of the hydrogeologic environment in which they are sited. In the context of landfill / ground water problems in U.S and elsewhere, the paper suggested possible strategies for landfill siting in South Africa. Following the 1991 paper, there were subsequent discussions and communications between the author and Division of Water Technology staff the CSIR about the risks posed by landfills. This report was commissioned to provide information about contamination risks from landfill leachate production in arid and semiarid areas of the U.S.

## 3 CONTENT OF THIS REPORT

The report includes several sections, each covering aspects of the landfill/ leachate problem related to arid conditions. Section 4. considers the basic landfill leachate problem. Section 5 gives attention to leachate production from landfills in dry climates. Section 6, on the vadose zone, is included because of the importance of vadose zone processes in arid area contamination. Section 7 is a brief statement concerning the hazardous nature of municipal solid waste, and Section 8 outlines some general aspects of landfill engineering. Section 9 discusses the fate of arid area precipitation, and Section 10 is a short comment on landfill siting. Monitoring networks are considered in section 11. In

Section 12, examples are provided of investigations in arid areas. Section 13 summarizes the conclusions. Section 14 includes text references and a list of additional sources used in the preparation of the report.

In deriving the correct conceptual models for arid area landfill sites, an appreciation of vadose zone hydrology is seen as particularly important. Work on arid area recharge has contributed to understanding of percolation processes above, within, and beneath landfills. Of additional importance to the arid area landfill leachate question are factors which may compromise the design integrity of the caps and liners of engineered landfills. Much of the US work on fill design and the prevention of ground water contamination has come from investigations for safe repositories for hazardous and low level nuclear waste. Given that municipal solid waste has the potential to produce toxic leachate, the hazardous waste siting criteria are of direct relevance. Data on arid area leachate production in the US are not freely available. Some unpublished consultant report information is presented from intensive studies of arid area landfills.

## 4 THE LANDFILL LEACHATE PROBLEM

Landfills containing municipal solid waste can have serious economic and ecological implications. The principal problem is the threat which landfill leachate can have on the integrity of ground water resources. (US EPA, 1986) Preventing, or reducing leachate generation from landfills can be expensive and the costs and benefits must be weighed against other social and infrastructure demands on the local or national tax base. Correct landfill siting, in order to reduce risk of aquifer damage if leachate leakage does occur, is likely to be particularly important for the next generation of waste disposal sites.

The issues of municipal solid waste reduction, and removal of hazardous waste from the domestic waste stream need to be components of any waste management strategy. Recycling, trash to energy and source reduction initiatives are extensively reported in the literature (US EPA, 1989a, 1989b). In most cases, the main concerns which drive the above initiatives are the environmental threats of ground water and surface water contamination. It is drinking water health risks, (real and perceived) in addition to ecological considerations, which influence most legislative and engineering endeavors to resolve the municipal solid waste disposal problem.

There is a rapidly expanding technology available for landfill engineering including liners, caps, gas collection and leachate collection/ treatment/ disposal systems. The technology comes with a high price tag which has considerably raised the costs of waste disposal with consequent economic impacts on community taxes. A major issue, which is not resolved, is to find an accepted basis for the calculation of the benefits in relation to the costs.

The parties involved in the issue, which include among others; local elected officials, municipal authorities, members of the public, landowners abutting landfill facilities, water resources managers, federal and state regulators, environmental groups and landfill owners and operators, all have different perspectives of risk, responsibility and most importantly of time frame. The time frame part of the debate is probably of much greater significance in semiarid environments where the cause and effect equation of contamination potential is slowed because of a reduced hydrologic dynamic. One of the major problems is the limited documentation of information about actual landfill leachate production.
"...Knowledge about the environmental impact (physical, chemical and biological) of landfills on adjacent surface waters and ground water is sparse" (Hogland, 1989 p 121).

## 5 SEMIARID LANDFILL LEACHATE

Arid areas are typically defined as areas receiving less than 250mm of precipitation (based on annual averages); the semiarid area precipitation threshold is between 250 and 500mm. There are several aspects to the semiarid/ arid area debate concerning landfills. There is the perspective that extensive landfill engineering using caps liners or leachate collection systems is unnecessary. The rationale for the minimum engineering concept is that annual average low precipitation amounts in such areas will be insufficient to produce much leachate. The rationale extends to the belief that even if moisture in the fill does generate some leachate in the landfill matrix, the dynamics of the hydrologic budget would not cause significant leachate outflow into the host geologic environment.

There are many articles about arid area hydrology which presume zero leachate production potential. Most are based on the assumption that there is no percolation of moisture below the zone where evapotranspiration effects occur. For example, a 1975 US EPA report on the use of the water balance method for predicting leachate generation from solid waste disposal sites, (Fenn, et al. 1975), concluded that landfills in arid areas presented no problems. Mann (1976) suggested that there is no direct recharge by rainfall through the vadose zone of arid regions. A paper by Falconer et al. (1982), reported that solutes remain in the upper non saturated zone of the geological profile in areas where the water balance is negative.

The Fenn report (Fenn, et al. 1975) presented model-generated data for three climatic areas. A theoretical "0mm" percolation figure was calculated for the semiarid Los Angeles area. This "no leachate" estimation influenced opinion in the U.S. during the late 70's and 80's about landfill design and the need for aquifer protection measures. Such viewpoints, now known to be incorrect, have unfortunately become entrenched in some official policy. The Fenn data are presented below in table 1.

TABLE 1. THEORETICAL PERCOLATION DATA (Fenn, et al., 1975)

| *PLACE* | *PRECIP* | *RUNOFF* | *INFIL* | *ET* | *PERC* |
|---|---|---|---|---|---|
| Cincinnati | *1025* | *154* | *872* | *658* | *213* |
| Orlando | *1342* | *100* | *1243* | *1172* | *70* |
| Los Angeles | *378* | *44* | *334* | *334* | *0* |

*(precip: annual average precipitation total in mm) (runoff: generated by the water balance model using assumptions about the thickness of a typical landfill daily cover) (infil: infiltration amount assumed to enter the landfill cover) (ET: actual evaporation based on theoretical models and average precipitation) (perc: amount of precipitation estimated to be entering the landfill)*
*(Fenn et.al. p18)*

The Fenn data were not supported by any empirical measurements and there are now many known instances of arid zone landfill leachate production which indicate that there are some serious flaws to the Fenn conclusion that "..leachate problems will be virtually non-existent at sanitary landfills in arid parts of the country." (Fenn, et al. 1975, page 22).

There are documented cases of recharge/ percolation in arid areas, for example in papers by Horton and Hawkins, (1965), and Sharma, (1987). Stephens, (1993) states that "there is no validity to the argument that recharge only occurs where annual precipitation exceeds potential evapotranspiration".

In 1985 the California State Water Resource Control Board initiated a program to measure municipal landfill leachate. The basis of the program is a site inspection called the Solid Waste Assessment Test (SWAT), (Parsons & Mulder, 1991). Of the 2200 known municipal solid waste refuse dumps in California, SWAT site investigations have been undertaken at 300 landfills throughout the state. Over 250 of the 300 landfills are producing leachate (Parsons, 1993a, 1993b). The annual average precipitation at 90% of the landfill sites is less than 375mm. For the most part, the landfills (some now closed) were constructed without clay liners. Of the closed landfills, none was protected with a post closure engineered impermeable cap. (Jones, 1993). From a sample of 126 of the sites where leachate leakage was found, 61% were shown to have caused adverse effects on the quality of adjacent "waters of the State" (Parsons & Mulder, 1991).

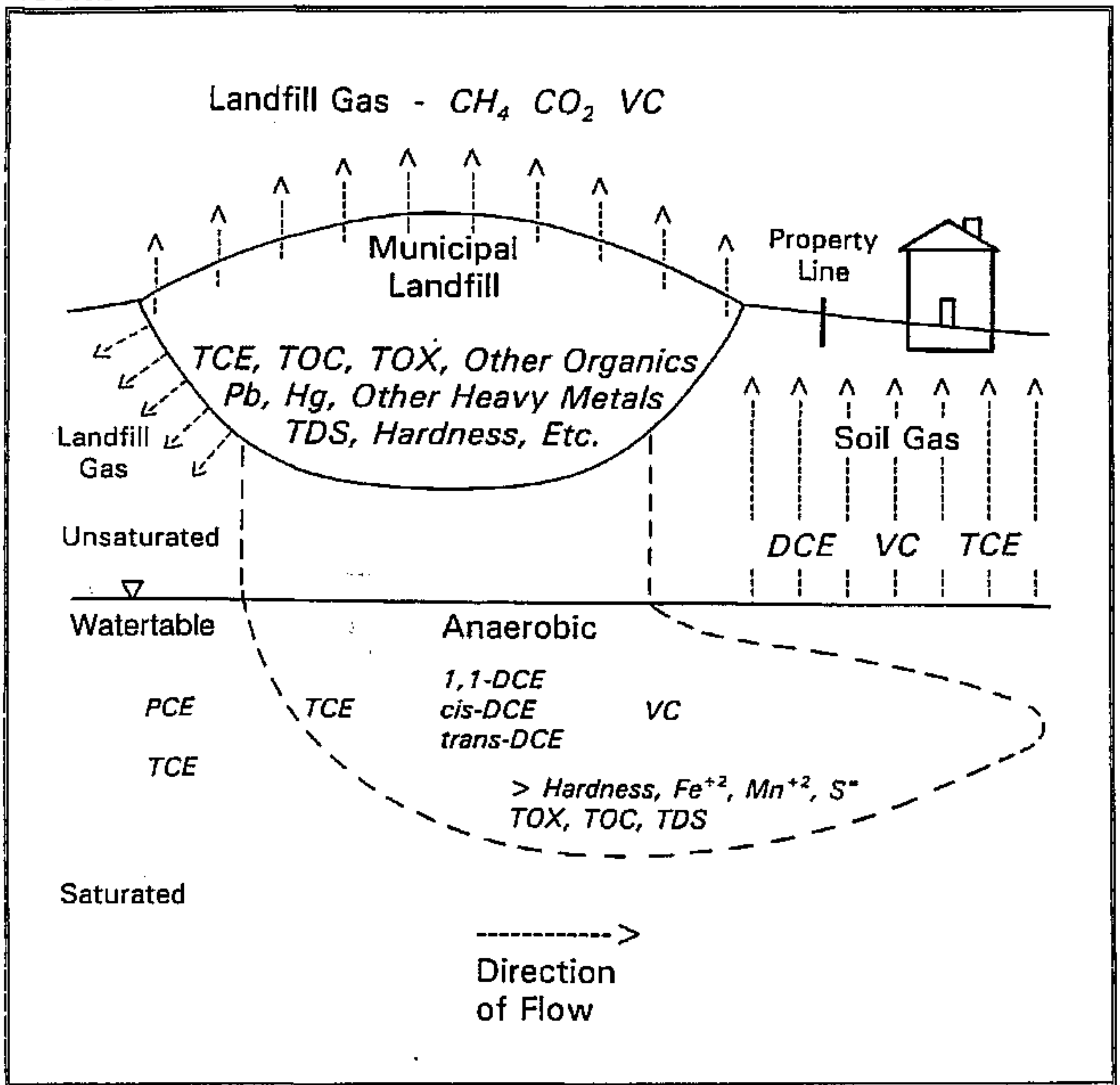
The low average precipitation figures of semiarid areas do not therefore provide an index of landfill leachate generation potential. Although much semiarid zone rainfall which infiltrates the soil will be removed by evapotranspiration, semiarid zone recharge events (percolation beyond the zone influenced by evapotranspiration) are not related to average (equivalent uniform depth) rainfall. (Wosika, 1993; Lee, 1993). Site specific macropore conditions will have an important influence on the downward migration of moisture. Recent vadose zone research demonstrates the ubiquitous occurrence of nonsaturated subsurface moisture movement. Movement of water (moisture) into, through and out of a landfill is not dependent on saturated flow. (See Vadose section below.) Figure 1 shows the typical conceptual model of environmental contamination risk from municipal landfills.

Nonsaturated movement of moisture is not the only vadose zone mechanism. Of particular importance is the capacity for landfills to generate and mobilize gaseous phase volatiles. Such gaseous movement of volatile organic compounds (VOCs) from landfills can migrate to, and contaminate groundwater. Such a landfill contamination occurrence has been reported for the Blythe Landfill in California (Perdue, 1993), where VOCs, but not the usual metals, have been detected in ground water over 100 feet below the level of the fill. This occurrence has taken place at the end of a seven year drought period.

## 6 THE VADOSE ZONE

Research over the last ten years has revealed much about the flow process in the unsaturated zone. It is widely accepted, (for example, Hillel, 1980) that soil water movements can occur at moisture contents which are much less than field capacity. Within the discipline of hydrogeology the new burgeoning field of vadose

FIGURE 1. ENVIRONMENTAL CONTAMINATION BY MUNICIPAL LANDFILLS




(from, Lee & Jones, 1991)

zone hydrology is necessitating reappraisals and rethinking concerning the traditional conceptual model that leachate production and movement is dependent on saturated flow conditions.

The vadose zone is that part of the geologic profile which lies above the zone of saturation. The zone of saturation may or may not be an aquifer, depending on permeabilities and interconnected storage. Flow in the vadose zone is dynamic with unsaturated flow occurring at differing degrees of partial saturation. There may be episodal periods of saturated flow. The vadose zone is not dry, it commonly contains interstitial water held by capillary and molecular forces. In porous and permeable rocks, insitu moisture will be only a small percentage of the total pore volume. In porous but generally impermeable rocks, the insitu moisture may represent up to 90% of the total pore volume. (Winograd, 1974).

All subsurface water (including moisture in the vadose zone) is part of the integrated subsurface hydrologic system. In ground water contamination work it is therefore more correct, and conceptually more desirable, to use the term sub-surface water in preference to ground water. Vadose zone contaminant movement may occur in nonaqueous, dissolved, gaseous and sorbed phases. In virtually every case, some form of nonsaturated subsurface water contamination will precede ground water contamination.

The matrix of solid waste material in a landfill can transport contaminants to the base of the landfill via unsaturated flow. Nonsaturated migrations in the gaseous phase are a normal ingredient of vadose zone moisture movement processes and nonsaturated movement may continue vertically in vadose formations beneath the landfill. Gases (water vapor and volatiles) can migrate both laterally and upgradient from landfills. Ground water contamination risk from contact with landfill gas therefore adds complexity to the conventional conceptual models of landfill hydrology and hydrodynamics.

Geochemical interactions can occur in the vadose zone and can be very complex. Ion exchange, oxidation/ reduction, hydrolysis, sorption, pH buffering, and biological degradation can all occur without saturation. Classic saturated Darcian gravity flow is not a prerequisite for subsurface hydrologic movements and associated contaminant migration. It is however very difficult to predict the attenuation and eventual location of contaminants in the vadose zone. (Neilson et.al., 1990)

The generation of leachate is not dependent upon the water table coming into contact with the fill material as was often proposed in landfill siting recommendations. Offsite transport of contaminants for any great distance however, is improbable without lateral saturated ground water movement.

## 7 LANDFILL CONTENT

The landfill and leachate generation topic can be considered under different scales of concern depending on the characteristics of the landfill content, the geological characteristics of its site, and the proximity to aquifers or streams which could be impacted.

If toxic leachate is hazardous to ground water integrity then it is reasonable to consider all municipal solid waste landfills as hazardous. Despite the existence of restrictions and controls, it is impossible to know what is deposited in landfills as part of the domestic waste stream. Even waste ingredients designated as benign, can, in combination with other so called benign refuse, produce toxic leachate. Added to this chemistry is the mix of toxic chemicals (paints, thinners, oils etc.) disposed of by the public within the domestic waste stream.

Many municipal landfills accept or have accepted, industrial waste, often in fluid form which has been added to the accumulated waste without any special provision for containment. This fluid waste may now be incorporated as moisture within the landfill solids content. There are in the U.S. thousands of municipal landfills (now closed) which were not sited in safe areas, which were not engineered in any way to achieve leachate minimization, and for which there are no reliable records of what was dumped.

Many presently active landfills, although now managed to minimize leachate generation, are sited above or alongside earlier landfill accumulations which did not receive any base liners and for which inadequate site geologic data were obtained.

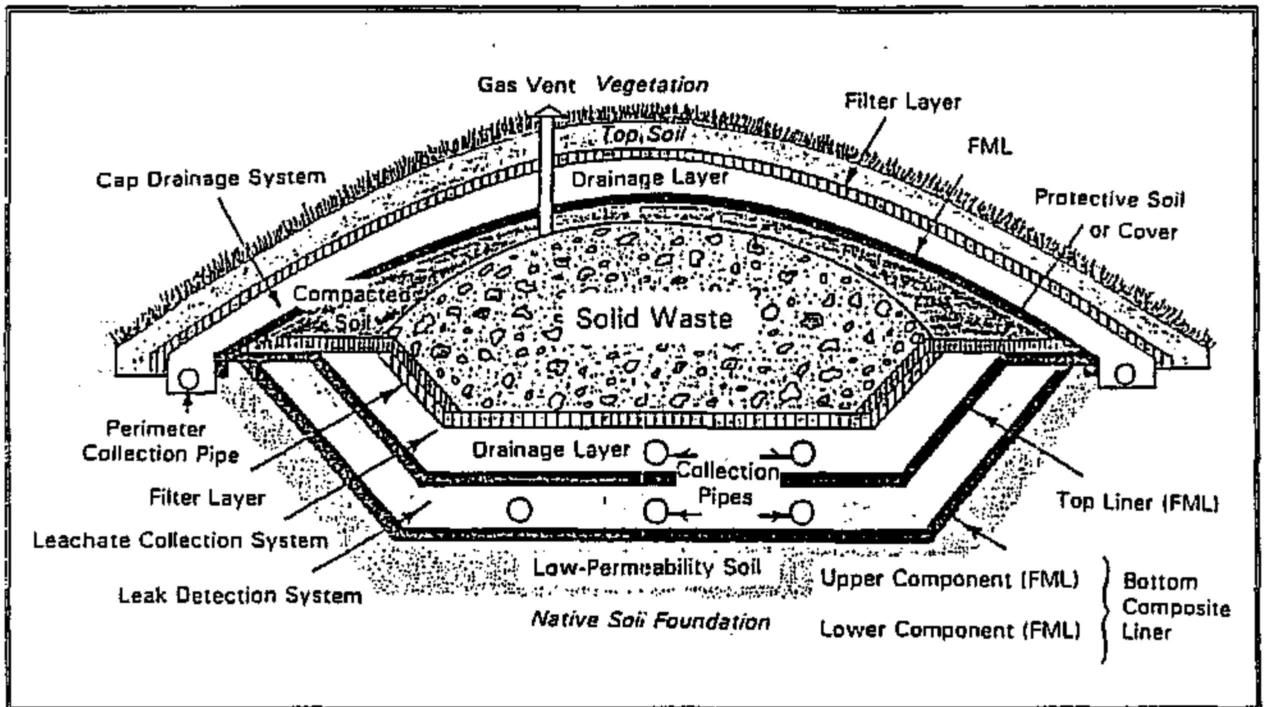
There is now a new generation of landfills which have been established in the last few years, which have been sited and designed, and are currently managed, in accordance with regulations and which are using state of the art technologies. Even these new landfills, while providing a high level of protection, do not represent a permanent, perpetually safe, waste disposal solution.

The notion that gas (methane) production only occurs when the landfill is capable of producing toxic leachate is incorrect (Lee & Jones, 1991), (Lee, 1993). The stabilization of fermentable organics and the diminution of gas from a landfill does not indicate that the solid waste no longer poses threats. The risk is there as long as the wastes are there. Although initial leachate production may be concentrated, there is not a specific period of time after the closure of a landfill in which there is a reduction in the potential to generate toxic leachate. Greater precautions taken to prevent water entering the landfill will lengthen the time before leachate problems may occur, but there is no reduction in the potential for the waste to generate leachate.

## 8 LANDFILL CAPS AND LINERS

Much of the research effort which has been undertaken concerning the integrity and performance of covers for fills has resulted from work on the safe disposal of low level nuclear waste. Although municipal solid waste is different in character, the problems involve the same principle of preventing the material from being incorporated in the sub-surface phase of the local hydrologic system. Literature on engineering design for designated hazardous sites and on nuclear waste repositories therefore has direct relevance to municipal solid waste landfill design discussions, for example Nyhan et al. (1990). Figure 2 shows the conventional generic design for an engineered landfill.

FIGURE 2 GENERIC DESIGN FOR AN ENGINEERED LANDFILL




(from Lee & Jones, 1991)

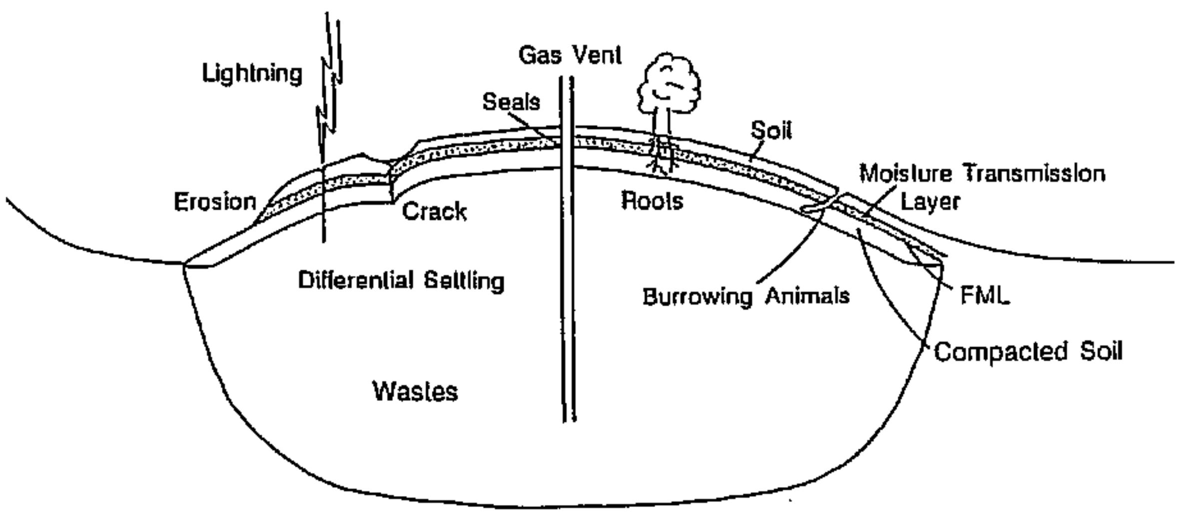
All landfills require site specific assessment of the potential for ground water contamination. In terms of risk assessment, there is no simple linear relationship between landfill size and leachate generation potential, the amount of leachate which will be generated or the toxicity of the leachate. Caps on landfills can effectively reduce the infiltration of precipitation through to the fill contents. Cap liner considerations in arid areas need to recognize the problems associated with burrowing rodents which can destroy the integrity of a cover (Hakonson, 1986). Clay impermeability is to an extent dependent on moisture content. Desiccation cracks on clay liners and caps in arid areas will increase permeability. A specific problem is that hard water can cause shrinkage in the montmorillonite clays often used as liners.

There is a great importance in the cap vegetation cover for increasing evapotranspiration, and in the minimization of infiltration and leachate production. The current layered cap design has resulted from simulations, experiments and field measurements, (Abeele, W.V. et. al. 1986)

Not even a properly constructed liner system can prevent contaminant movement. Organic contaminants can be absorbed by the liner and desorb on the other side. This can occur with low molecular weight chlorinated solvents such as TCE. (Haxo, 1988)

The purpose of a landfill cover is to isolate buried wastes (Nyhan et.al. 1990). Inadequate design or maintenance can lead to cap erosion, increased infiltration and leachate generation. Increased fill subsidence and cause uneven settling and create further reduce cap impermeability. Control of the internal water balance is the principal guiding post-closure landfill management. The difficulty is to quantify the fill's internal water balance in order to determine the appropriate management techniques. There have been many documented landfill failures (Hakonson et.al. 1982). The siting and design of many landfills was often based on an inadequate hydrological conceptual model. Figure 3 shows some of the aspects of landfill design that pose a threat to the long term integrity of caps in keeping moisture out of landfill.

FIGURE 3 THREATS TO THE LONG TERM INTEGRITY OF LANDFILL CAPS




(from Lee & Jones, 1991)

The calculation of leachate production in a landfill needs to be by measurement, and not by difference estimates between precipitation and evapotranspiration. Small field errors of evapotranspiration will give large predicted leachate errors. Longmire reports that 96% of precipitation received on caps is returned by evapotranspiration in a semiarid area of New Mexico (Longmire and Gallagher, 1981). In terms of cap design, a capillary barrier can reduce leachate generation. Most caps have differently engineered layers to prevent deep root growth. Plant roots penetrating through the cap could promote translocation of materials and increase secondary permeabilities.

Typical landfill design includes a bottom liner which is overlain by a leachate collection system consisting of a drainage layer and piping, a leachate collection and removal system (Figure 2). The purpose is to prevent leachate from contaminating ground water. In the northeast of the US the percolation rate into operating landfills varies from 10 to 20 inches per year. (Oweis and Biswas, 1993). For semiarid areas, a bottom liner and a leachate collection system may serve a valuable purpose during the operation of the landfill when the fill is particularly vulnerable to infiltration from storm rainfall.

Most older landfills have no bottom liner and the refuse base in direct contact with geologic materials. On modern fills the base liner is on stable materials, but the cap is likely to be subject to subsidence with settling and decomposition within the landfill. Settlements of up to 50% of the refuse material have been reported (Jaros, 1991). Settlement could influence leachate generation. Overall landfill vertical displacement can be up to 27% (Cosduto and Huitric, 1990). It is possible that compaction could squeeze out leachate from the fill material. Theoretically, landfill field-capacity will increase as pore sizes decrease during consolidation. Compaction will reduce the macropore size within fill material, and in saturated portions of a fill would therefore provide more surface area of fill material for leaching. Surface macropore openings and threats to the integrity of the cap resulting from displacement may be far more important concerns for increasing the risk to aquifers from leachate generation.

## 9. RAINFALL / PRECIPITATION

Conflicting opinions exist about the generation of leachate in arid areas. It is technically invalid to suggest that because the regional net water balance is negative, no leachate will be generated (Lee and Jones, 1991). For arid area landfills, the short term net water balance for a predicted event of particular magnitude should be calculated, and those data should be applied to the calculation of the landfill water balance. Models such as HELP can be used for predictive purposes. The HELP model which simulates landfill infiltration is applicable to landfill cap design under ideal conditions. The HELP model, (Hydrologic Evaluation of Landfill Performance) is particularly useful for obtaining design information (Schroeder et al. 1984). The HELP model (version 2.5) is a quasi two dimensional model developed to estimate: infiltration, runoff, lateral drainage, vertical percolation and seepage. The model considers the effects of precipitation, runoff, infiltration, percolation, evapotranspiration, drainage and soil characteristics. The soil characteristics include moisture content, field capacity, wilting point, porosity and saturated hydraulic conductivity.

The HELP model is widely used as a tool for U.S. landfill studies. It is simple to use and can incorporate components of lateral flow within the landfill. A major drawback is that the model does not account for deterioration in the design performance of the cap caused by for example, clay desiccation, rodent damage, settling deformations, or even imperfections in the flexible membrane liner (FML) if installed as part of the cap design (Figure 2). This means that in practice, model runs incorporate data from design specifications rather than using data for the potential deteriorated field conditions which may be expected several tens of years after landfill closure. An occasional direct hit from a cloudburst is not an impossible occurrence for a landfill in arid areas. Such an occurrence, on a fill with an ineffective cap would drastically change the landfill moisture balance predictions. The stochastic occurrence of extreme precipitation events is not usually factored into model runs to predict percolation.

The U.S. Nuclear regulatory commission requires a site hydrological model as part of the license application process. Being able to quantify and predict the hydrologic performance of shallow land burial facilities important for design, closing and monitoring of landfills. The CREAMS model (Chemicals, Runoff, Erosion from Agricultural Management Systems), developed by the US Department of Agriculture (Knisel, 1980) has been used for fill design simulation (Devaurs & Springer, 1988).

Selection of parameter values is difficult in the application of the CREAMS model to semiarid sites. Estimating upper limits for precipitation input parameters is important for predictive purposes. The model assumes that hydrologic processes provide the transport medium for contaminants. CREAMS can use daily or storm rainfall data. It requires data on antecedent conditions, and in an appropriate feature for landfills, can use up to seven different soil layers characteristics. The model is essentially a one dimensional model which calculates the vertical transport of water in a soil column.

The vertical movement of water through a cap layer can be described as :- ds/dt = P - Q - ET - L, where ds/dt is change of vadose moisture content over time, P is precipitation, Q is runoff, ET is evapotranspiration, L is seepage and t is time. CREAMS can simulate observed trends but does not account for non-saturated flow.

The greatest vulnerability of landfills to water inputs from precipitation occurs throughout the duration of landfill operation. The size of uncapped working area of landfill surface is of particular importance because of high permeabilities. As indicated in discussion above, precipitation input to water balance equations in semiarid areas needs to involve the probabilities of extreme event rainfall. High intensity short duration rainfall events will be of greater significance in impacting working fills, whereas for closed fills which have a cap or surface seal, it is the long duration low intensity event which would produce the greatest potential for overall infiltration through the cap surface. For closed landfills which have defective covers / caps, or which are not adequately hydrologically isolated from surface flow, the high intensity rain events may provide the most favorable opportunity for water inputs to the fill.

In order to assess the potential for landfill contamination in semiarid areas, site specific information is needed on subsurface water flux and potential for leaching. Knowledge of the site geomorphology, and the characteristics of soils and geology will be of prime importance. Leaching and translocation of waste contaminants to ground water is not considered very likely in semiarid and arid regions under normal circumstances. (Aguilar and Aldon, 1991). However, the potential for macropore water movement, and the possibility of increased percolation opportunity from surface runoff concentration or ponding, can provide localized exceptions for may different geological situations. Unusually severe precipitation events could result in saturated flow and contaminant migration especially if the precipitation event is of long duration and low intensity. In Aguilar's work in New Mexico, the mean annual precipitation was 400mm and the sub-surface water flux was primarily due to vapor equalization processes.

## 10 LANDFILL SITING

Prevention of the development and the release of leachate by isolation of the landfill contents from the hydrological system is the main design criteria for safe landfills, (Longmire, 1981). A more detailed summary is provided in the paper by Stone, (1991).

The principal factor in siting and design considerations for landfills is the prevention of surface water and aquifer contamination. In developing siting and design plans a distinction needs to be made between ground water contamination and aquifer contamination. It may be acceptable, from the perspective of pragmatic economics, to have some risk of ground water contamination, provided there is no risk of contaminant migration which will result in aquifer contamination. Two guiding principles for landfill siting are that meteoric water should be prevented from entering the landfill; and that the host rock permeability must be low. A site which has zero rock permeability however could exacerbate the risk of surface water contamination from a landfill. In general terms however, any condition which make a site suitable for ground water supply is likely to make it highly unsuitable as a site for waste disposal.

## 11 MONITORING NETWORKS

Monitoring has become an integral part of landfill site studies. Regulatory requirements for site characterization and the need for subsurface aqueous and nonaqueous chemical data have increased attention to methods of environmental monitoring. However not all of the 6600 MSW Landfills in the U.S. are currently monitoring ground water. Recognition of the longitudinal dispersion of leachate rather than as a tongue with an appreciable horizontal component is an important consideration in design of monitoring networks. Density differences between leachate and regional ground water may produce leachate plumes within, and often at the base of ground water flow systems. An integrated sample from a fully penetrating screened monitoring well may become too dilute from non contaminated flow. In arid climates, leachate release will not be constant, making detection difficult. An additional problem in damp but not saturated monitoring systems is the plugging of observation network piping by biological growth (Koerner, 1989).

Work in California (Parsons & Mulder, 1991) recognizes the limitations of monitoring, especially when groundwater water levels fall below the drilled depth of monitoring wells during drought periods. A section taken from the SWAT Report illustrates an additional problem of sampling from monitoring wells. "In most cases, volatile organic compounds are the main waste constituents that are detected, primarily vinyl chloride, trichloroethylene, methylene chloride and benzene. These sites may also be leaking [other] hazardous waste, but the concentration of constituents in the leakage has been diluted below hazardous waste levels by the time the constituents are detected at monitoring points. Monitoring points are rarely near enough to the waste leakage source or migration pathway to detect the maximum concentrations. Also, a contaminant plume may migrate in pulses following storm events, thereby making the timing of sample collection a factor in the concentration levels detected." (Parsons & Mulder, 1991, p 26).

Monitoring requirements increase municipal landfill operation costs. In humid areas where the background ground water flow characteristics are more dynamic and predictable, the siting of monitoring wells is easier than in arid areas which often have deeper water tables and less predictable flow regimes. The purpose of monitoring is to provide data for management decisions and it is important that the data are representative. The main siting difficulty is to place monitoring wells in locations where contaminants are most likely to occur and be detected. Absence of contaminant traces however only means that there is no detection in the capture zone of the measured well. It may indicate that the monitoring well missed the plume, that leachate migration was not occurring in saturated flow conditions, or that the sampling occurred between pulses of leachate movement.

There have been cases where the detection of contaminants in ground water is falsely attributed to leachate leakage from a landfill. Certain compounds, when found in monitoring wells are usually regarded as indicators of contamination. Water soluble leachates can be considered as either organic or inorganic compounds. Six common inorganic readily leachable ions are chloride, sodium, iron, calcium, ammonia and sulphate. Boron, iron, ammonia and TDS have been found to be useful as indicators of leachate contamination (Clarke and Piskin, 1977), although these do also occur naturally.

A change in background chemistry of a well near a landfill may not necessarily mean that leachate is reaching adjacent aquifers. Misinterpretation of data can occur. For example, in a case reported by Ulhman, increased boron & sulphate levels were initially interpreted to indicate landfill liner failure. However further investigation demonstrated that the concentration increases resulted from natural chemical processes because of changed hydraulic gradients caused by the areal extent and volume of the landfill facility. The changes were not caused by any leakage from the landfill (Ulhman, 1991).

Where leachate occurrence is confirmed, variations in leachate quality and concentration may result from natural background ground water quality variations. Data need to be very carefully analyzed. Milke and Huitric, (1993) report on new simulation techniques for determining false negative errors (the probability of undetected ground water contamination) A false positive suggests that ground water is contaminated when in fact it isn't.

For an arid site in Southern California Reaber and Todd (1990) report that the landfill monitoring strategy includes conventional ground water monitoring wells and also vadose access tubes. The soil chemistry measured is similar to background ground water chemistry and the data provide no evidence of contamination.

Up to now much of the scientific and engineering response has been reactive to the problems resulting from past landfill practices. New landfills, and increased awareness of problems, now provide an opportunity for proactive monitoring (Kramer et al. 1991) Most new landfills have leachate collection and retrieval systems (LCRS). At new Californian facilities the installation of access tubes beneath the landfill has become standard practice (Parsons, 1993).

Detecting ground water contamination from water samples from monitoring wells is a conventional approach. However if the site conditions allow, sampling from the vadose zone before contaminants can reach the ground water, would provide an earlier warning of contamination (Cullen et. al., 1992). Vadose zone hydrogeology is particularly important in the more arid areas where depth to ground water may be greater. Relatively simple low cost techniques such as neutron moderation, dielectric measurements, and soil gas screening can provide more, and more meaningful data than conventional fluid samples. If all moisture movement into, through, and out of a landfill is in the nonsaturated phase then conventional monitoring wells would not produce any data, and there may be a falsely presumed safety.

## 12 RECHARGE / LEACHATE IN ARID ENVIRONMENTS

Recharge is generally defined as the rate at which water replenishes an aquifer. In many arid areas recharge was thought only to occur in ephemeral stream channels and in places where the geomorphological configuration of landscape may concentrate precipitation. Recharge may be highly localized in arid areas, and may take place where permeable rocks, or fracture zones occur at or near the surface. Ground water discharge typically occurs to stream channels in low lying areas. According to some research, there is evidence that little or no direct infiltration of precipitation to the water table takes place in the gently sloping plain interfluve areas in the arid parts of the U.S. (Winograd, 1974). Clyde (1981) in work on the contamination potential on alluvial fans concluded that because of lack of recharge, deep aquifers were not at risk from contamination.

The issue of a more diffuse recharge in arid and semiarid areas has significance for the landfill leachate generation problem. There is evidence that diffuse recharge can occur in low rainfall areas. For example in the Colorado high plains some 60mm of recharge was estimated in an area with an average precipitation of 400mm. (Longenbaugh, 1975, 1993). Other arid zone estimates quoted in

Stephens and Knowlton, (1986) indicate considerable evidence for the occurrence of diffuse aquifer recharge.

A field research investigation in southern New Mexico, where mean annual precipitation is 200mm and potential evapotranspiration is 1780mm, demonstrated deep infiltration of between 7mm and 37mm of the precipitation over a 19 month period (Stephens and Knowlton, 1986). While acknowledging the possible sources of error in the field experiment methodology, the authors concluded that winter frontal storms and summer thunderstorms led to deep infiltration and presumably to ground water recharge. For purposes of siting waste disposal facilities, it is important to quantify soil water movement under natural conditions (Stephens and Knowlton, 1986).

In an unpublished report, Stephens (1993) cites various research data concerning precipitation, evapotranspiration and recharge. A selection of the information is summarized in table 2.

TABLE 2 RESEARCH DATA FOR RECHARGE IN ARID AREAS

| *SITE* | *PRECIP* | *EVAPOT* | *RECHARGE* | *REFERENCE* |
|---|---|---|---|---|
| | <------------ | mm | ----------> | |
| *Socorro New Mexico* | *190* | *1780* | *7 - 37* | *Stephens & Knowlton 1991* |
| *Las Cruces New Mexico* | *230* | *1780* | *1.5 - 9.5* | *Phillips et al. 1992* |
| *Hanford Washington* | *160* | *1400* | *0 - 100* | *Gee et al. 1989* |
| *Curry County New Mexico* | *444* | *1156* | *0.2 - 2.8* | *Stone 1986* |
| *Beatty Nevada* | *74* | *1900* | *0.036* | *Nichols et al. 1987* |
| *Hudspeth Texas* | *280* | *1960* | *0.01 - 1* | *Scanlon et al. 1991* |
| *Saudi Arabia* | *70* | *2400* | *20* | *Dincer et al. 1974* |
| *Eastern Botswana* | *447* | *1220* | *0.5 - 6* | *Carlsson et al. 1989* |
| *Southern Cyprus* | *390* | *1450* | *10 -94* | *Kitching et al. 1980* |

Table from unpublished information from Stephens (1993)

## . COLORADO EXAMPLE

From an intensive ongoing study of a landfill in Colorado, information relevant to semiarid conditions is presented below. (Anon, 1993). The Denver-Arapahoe Disposal Site is about 20 miles southeast of Denver. It now receives 25-30% of refuse generated in the Denver Metropolitan area. It was established as a municipal solid waste landfill, and began operations in 1966. Contaminants were found during 1980 investigations of surface water and ground water. Disposal practices were then changed. Interim remedial measures included a barrier collection system to eliminate off-site migration A four foot thick cover has been emplaced to prevent infiltration. Precipitation averages 300mm to 350mm per year.

Background geology indicates low permeability claystone and shale units. The regional aquifer systems produce potable water and there are 90 wells within 3 mile radius. Neither shallow wells nor deeper municipal wells have any evidence of contamination.

The information below which is summarized from the site investigation study, needs to be seen in the context of the previous sections of this report.

- The landfill content was virtually all unsaturated with no significant perched liquid found in the landfill.
- Within the fill content there was no distinct areal or vertical distributions for metals in unsaturated solids samples.
- Monitoring wells and soil studies showed no evidence of current leachate migration from the landfill.
- There was some evidence of past leachate migration in sand stringers but this was probably related to leachate production contemporary with the fill operation.
- Although the landfill is not saturated, the concentration of volatiles is greater lower in the landfill column. This may result from the lower fill being older and having a greater moisture content.
- The moisture content of solids above the water table is substantially lower than the field moisture capacity of the fill material.
- Data from the HELP model indicate that currently no significant infiltration to the landfill is taking place.

- The evaluation of the contamination potential of unsaturated solids is difficult because municipal solid waste is complex in content.
- The landfill volume is 98% unsaturated. The moisture content ranges from 7.9 to 50.4% . Moisture content of the landfill is 41% in the upper 0-5 ft level, and declines until the 70 foot level, and then increases to the base of the fill.
- Leaching tests on fill material confirm the landfills toxicity potential. it is recognised that macropore flow within fill would be less effective at producing leachate than laboratory saturation experiments.
- The overall porosity of the landfill is 64%.
- The HELP model estimates 92.12% of precipitation on the landfill is lost to evapotranspiration, and 7.35 to runoff.
- Systematic percolation through the cap is considered unlikely.

## . NEW MEXICO CASE STUDY

The HELP model (version 2.50) was recently used (Stephens and Coons, 1993) to predict the rate of seepage from a proposed landfill in New Mexico. The average precipitation at the site is 200mm and potential evapotranspiration is 1270mm. The work was undertaken for a proposed landfill operation of 80 years, a working top layer of 15cm thick bare compacted soil, and a final protective cap of 61 cm of compacted soil. Some grass cover was assumed for the final cap. The model attempted to predict the deep percolation component of the site water balance equation.

The HELP model prediction for deep percolation was ($4 \times 10^{-11}$ cm/s) after 80 years of operation. The percolation would increase to $6.3 \times 10^{-10}$ cm/s) after 1,200 years. The model further predicts that for the next 3,000 years the percolation rate decreases until it equilibriates at ($2.2 \times 10^{-10}$ cm/s). In the overall water balance the deep percolation which would become recharge is 0.034% of the mean annual precipitation.

The results of the theoretical assessments show that the long term fluxes of moisture through landfills in the researched area would be small. The authors note however that their conclusion is only valid for properly designed and managed solid waste landfills which do not allow free liquids to be dumped in to the fill, and which are engineered to prevent other hydrological input (Stephens and Coons, 1993).

## 14 CONCLUSIONS

The "jury is still out" with regard to the effectiveness of leachate prevention by engineered covers and liners for landfills in arid areas (Stephens, 1993). There has just not been enough time to test the effectiveness of recent improvements to arid area design criteria. Ironically the use of liners can make leachate detection more difficult because leakage will be concentrated rather than diffuse. There are proposed new mega-landfills in California for which the generation of volatiles is presumed to be a certainty. Isolation of vadose moisture, as fluid or gas, from groundwater is a major design and management consideration (Perdue, 1993). For most researchers the issue of leachate generation from municipal solid waste landfills is regarded as one of "when, rather than, if". The traditional "dry-tomb" approach to the disposal of municipal solid waste has been extensively reviewed by Lee & Jones (1991) and is seen by them as only an intermediate solution to municipal solid waste disposal.

The basic conclusion from the review of literature is that landfills in arid areas do have the potential to impact aquifers. The concept of landfill safety because annual potential evaporation exceeds annual precipitation is demonstrated to be false. The use of engineered caps and liners can be very effective in reducing and delaying the contamination risks.

The three most important performance and environmental aspects of landfills appear to be siting, siting and siting. If properly engineered landfills can be sited in an appropriate geological host, and in an area isolated from aquifers there need not be an adverse water resources impact. There are engineering designs which can be very effective at ensuring safe storage and containment, the critical aspect is the time factor of the duration of "safe" conditions.

For many landfills in more humid areas, the natural dilution of leachate in a dynamic aquifer system has been an effective means of solving a problem. The issue with arid areas is that there are not usually excess ground water flows to assist with chemical transformations and dilutions below maximum permitted contaminant levels. A compounding factor is that because of the dry climate, ground water may be the sole source available for use.

An important new concept in decision making could be the (MCDM) Multi Criterion Decision Making method which finds the most appropriate management strategy by ranking the alternatives. The management of aquifers and the need to avoid contamination from landfills needs to address the conflicting issues of environmental quality, resource availability and economics. There is no longer a single objective, and conflicting demands must be satisfied at some level of hydrologic/ economic/ ecological compromise. The concept of a non-dominated solution of MCDM is one in which there is no other feasible solution that will cause an improvement in any one of the objectives without making at least one other objective worse (Shafike, 1992). Perhaps a particularly important concept in landfill contamination issues?

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