LANDFILLING OF WASTE: LEACHATE

Edited by

T. H. Christensen • R. Cossu • R. Stegmann

Taylor & Francis
Taylor & Francis Group

Landfilling of Waste: Leachate

Landfilling of Waste: Leachate

Edited by

T. H. CHRISTENSEN
Department of Environmental Engineering
Technical University of Denmark
Lyngby, Denmark

R. COSSU
Institute of Hydraulics
University of Cagliari
Cagliari, Sardinia, Italy

R. STEGMANN
Institute of Waste Management
Technical University of Hamburg-Harburg
Hamburg, Germany

Taylor & Francis
Taylor & Francis Group
LONDON AND NEW YORK

Taylor & Francis
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

First edition 1992 by Taylor & Francis

Reprinted 1997 (twice) by Taylor & Francis

Transferred to Digital Printing 2005

ISBN 0 419 161406

A Catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data 91-35776 CIP

Preface

During the last couple of decades landfilling of waste has developed dramatically and today in some countries involves fully engineered facilities subject to extensive environmental regulations. Although much information and experience in landfill design and operation has been obtained in recent years, only a few landfills meet the current standards for an environmentally acceptable landfill. In view of the increasing public awareness and new scientific understanding of waste disposal problems, the standards for landfilling of waste may improve even further within the years to come.

In view of this great demand for information on landfills we decided to establish, as Editors, a series of international reference books on landfilling of waste. No worldwide, long tradition of publishing information on landfilling exists and this book series is seen as an attempt to establish a common platform representing the state-of-the-art, useful for implementing improvements at actual landfill sites and for identification of new directions in landfill research.

This first book deals with leachate, the strongly contaminated wastewater developing in landfills. Aspects such as landfill hydrology, leachate characterization and composition, factors controlling leachate quality, principles of leachate treatment, and effects of leachate in groundwater are discussed in great detail. The introductory chapter presents an overview of the main aspects covered in the book. Some of the contributions in the book may express different opinions and strategies, allowing the reader to develop his own balanced views. Leachate collection, including liner and drainage systems, is not described in this book, but is the topic of a following book.

This book on leachate consists of edited, selected contributions to the International Symposia on Sanitary Landfills held in Sardinia (Italy) every second year and of chapters specially written for this book. The responsibility for the technical content of the book primarily rests with the individual authors and we cannot take any credit for their work. Therefore reference should be made directly to the authors of chapters. Our role as Editors has been one of reviewing and homogenizing the chapters and of making constructive suggestions during the preparation of the final manuscripts.

We would like to thank all our contributors for allowing us to edit their manuscripts and ask for everybody's forbearance with our unintended mistreatment of the English language. For this reason we would like to give credit to Elsevier Science Publishers for correcting the English where necessary and for giving shape to the book.

Finally we would like to thank Ms Anne Farmer at CISA, Cagliari, for her patient indispensable work on the many drafts of the book.

Thomas H. Christensen
Raffaello Cossu
Rainer Stegmann

Contents

2 LEACHATE PRODUCTION AND COMPOSITION

3 LEACHATE TREATMENT

4 ENVIRONMENTAL ASPECTS OF LEACHATE

List of Contributors

L. Ahnert
Universität Wuppertal, Abfall- und Siedlungswasserwirtschaft, Pauluskirchstrasse 7, D-5600 Wuppertal, Germany

H. Albers
Ingenieurbüro Dr Born – Dr Ermel, Finienweg 7, D-2807 Achim-Baden, Germany

G. Andreottola
CISA, Environmental Sanitary Engineering Centre, Via Marengo 34, I-09123 Cagliari, Italy

F. Avezzù
Department of Environmental Sciences, University of Venice, Calle Larga Santa Marta, Venice, Italy

P. Baccini
Swiss Federal Institute of Water Resources and Water Pollution Control, CH-8600 Dübendorf, Switzerland

J. M. Ball
University of the Witwatersrand, P O Wits, 2050 I, Jan Smuts Avenue, Johannesburg, South Africa

C. Barber
CSIRO, Groundwater Research, Wembley, WA 6014, Australia

H. Belevi
Swiss Federal Institute of Water Resources and Water Pollution Control, CH-8600 Dübendorf, Switzerland

G. Bissolotti
SIAD SpA, Via San Bernardino 92, I-24100 Bergamo, Italy

N. C. Blakey
Water Research Centre plc, Medmenham, PO Box 16, Marlow, Bucks, UK, SL7 2HD

G. E. Blight
University of the Witwatersrand, PO Wits, 2050, 1 Jan Smuts Avenue, Johannesburg, South Africa

P. Cannas
CISA, Environmental Sanitary Engineering Centre, Via Marengo 34, I-09123 Cagliari, Italy

T. H. Christensen
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

C. Collivignarelli
Department of Civil Engineering, University of Brescia, I-25060 Brescia, Italy

R. Cossu
Institute of Hydraulics, University of Cagliari, Piazza d'Armi, I-09123 Cagliari, Italy

P. Courant
France Dechets, F.D. Conseil, 71 rue Henri Brettonet, F-78970 Mezieres-sur-Seine, France

H. Doedens
Institut für Siedlungswasserwirtschaft und Abfalltechnik, Universität Hannover, D-3000 Hannover, Germany

H.-J. Ehrig
Universität Wuppertal, Abfall- und Siedlungswasserwirtschaft, Pauluskirchstrasse 7, D-5600 Wuppertal, Germany

M. Ettala
Department of Environmental Sciences, University of Kuopio, PO Box 1627, SF-70211, Kuopio, Finland

A. Foverskov
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

R. Gillham
Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

K. Hasselgren
Department of Civil Works, S-268 80 Svalöv, Sweden

D. J. Hojem
University of the Witwatersrand, PO Wits, 2050, 1 Jan Smuts Avenue, Johannesburg, South Africa

F. Holz
Haase Energietechnik GmbH, Gadelander Strasse 172, D-2350 Neumünster, Germany

A. Jaap
Euroconsult, PO Box 441, NL-6800 AK Arnhem, The Netherlands

J. M. Jans
Euroconsult, PO Box 441, NL-6800 AK Arnhem, The Netherlands

P. Kjeldsen
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

K. Knox
Knox Associates, 21 Ravensdale Drive, Wollaton, Nottingham, UK, NG8 2SL

P. Kristensen
Water Quality Institute, 11 Agern Allé, DK-2970 Hørsholm, Denmark

G. Krückeberg
Abfallentsorgungsbetrieb des Kreises Minden–Lubbecke, Pohlsche Heide, D-4955 Hille 1, Germany

J. La Cour Jansen
Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark

T. Larsen
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

R. G. W. Laughlin
Ortech International, 2395 Speakman Drive, Mississauga, Ontario, Canada L5K 1B3

U. Lund
Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark

J. Lyngkilde
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

P. J. Maris
Monitor Environmental Services, 3 Dewpond Close, Stevenage, Herts, UK, SG1 3BL

N. Millot
Labo Services, Route de la Centrale, F-69700, Givors, France

F. E. Mosey
Water Research Centre plc, Medmenham, PO Box 16, Marlow, Bucks, UK, SL7 2HD

A. Muntoni
CISA, Environmental Sanitary Engineering Centre, Via Marengo 34, 09123 Cagliari, Italy

K. Nilsson
VBB VIAK, Division for Water & Environment, Geiersgaten 8, S-216 18 Malmö, Sweden

S. O'Hannesin
Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1

P. Østfeldt
Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark

F. G. Pohland
Department of Civil Engineering, 949 Benedum Hall, University of Pittsburgh, Pittsburgh, PA 15261, USA

L. Rasmussen
Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark

H. Robinson
Aspinwall & Company Ltd, Walford Manor, Baschurch, Shrewsbury, UK, SY4 2HH

H. Segato
Water Quality Institute, Agern Allé 11, DK-2970 Hørsholm, Denmark

R. Serra
CISA, Environmental Sanitary Engineering Centre, Via Marengo 34, 09123 Cagliari, Italy

B. Skov
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

R. Stegmann
Institute of Waste Management, Technical University of Hamburg-Harburg, Harburger Schlossstrasse 37, D-2100 Hamburg 90, Germany

U. Theilen
Institut für Siedlungswasserwirtschaft und Abfalltechnik, Universität Hannover, D-3000 Hannover, Germany

P. J. Top
Ortech International, 2395 Speakman Drive, Mississauga, Ontario, Canada L5K 1B3

A. Van der Schroeff
Euroconsult, PO Box 441, NL-6800 AK Arnhem, The Netherlands

V. Vanek
VBB VIAK, Division for Water & Environment, Geiersgaten 8, S-216 18 Malmö, Sweden

G. P. Vicevic
Ortech International, 2395 Speakman Drive, Mississauga, Ontario, Canada L5K 1B3

B. Weber
Haase Energietechnik GmbH, Gadelander Strasse 172, D-2350 Neumünster, Germany

1. LANDFILL LEACHATE: AN INTRODUCTION

1 Landfill Leachate: An Introduction

THOMAS H. CHRISTENSEN
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

RAFFAELLO COSSU
Institute of Hydraulics, University of Cagliari, Piazza d'Armi, I-09123 Cagliari, Italy

&

RAINER STEGMANN
Institute of Waste Management, Technical University of Hamburg-Harburg, Harburger Schlossstrasse 37, D-2100 Hamburg 90, Germany

INTRODUCTION

The sanitary landfill plays a most important role in the framework of solid waste disposal and will remain an integral part of the new strategies based on integrated solid waste management.

The quality of landfill design, according to technical, social and economic development, has improved dramatically in recent years. Design concepts are mainly devoted towards ensuring minimal environmental impact in accordance with observations made concerning the operation of old landfills.

The major environmental concern associated with landfills is related to discharge of leachate into the environment and the current landfill technology is primarily determined by the need to prevent and control leachate problems.

LEACHATE PROBLEMS IN LANDFILLS

The most typical detrimental effect of leachate discharge into the environment is that of groundwater pollution. To prevent this, the first step in landfill design development was to site the landfill far from the groundwater table and/or far from groundwater abstraction wells. Thus more attention was focused on studying the hydrogeology of the area in order to identify the best siting of the landfill.

A further step in landfill technology was to site the landfill in low permeability soil or to engineer impermeable liners to contain wastes and leachate. Containment, however, poses the problem of leachate treatment. Nowadays the leachate control strategies involve not only landfill engineering but the concept of waste management itself.

Leachate pollution is the result of a mass transfer process. Waste entering the landfill reactor undergoes biological, chemical and physical transformations which are controlled, among other influencing factors, by water input fluxes. In the reactor three physical phases are present: the solid phase (waste), the liquid phase (leachate) and the gas phase. The liquid phase is enriched by solubilized or suspended organic matter and inorganic ions from the solid phase. In the gas phase mainly carbon (prevalently in the form of CO_2 and CH_4) is present.

Discharge of leachate into the environment is nowadays considered under more restrictive views. The reasons for this are:

- Many severe cases of groundwater pollution at landfills.
- The greater hazard posed by the size of landfill which is larger than in the past.
- The need to comply with more and more restrictive legislation regarding quality standards for wastewater discharges.
- With integrated waste management strategy the volume of refuse will be reduced but more hazardous waste may need to be landfilled, e.g. combustion residues, hazardous components consequent to separate collection, etc.
- More and more often landfills are located on the ground or on a slope and in both cases accumulation of leachate may be a negative factor with respect to geotechnical stability.

The leachate problem accompanies landfill from its beginning to many decades after closure. This means that leachate management facilities should also last and their effectiveness be ensured over a long period of time—so far, this still remains to be proven.

LEACHATE CONTROL STRATEGIES

In view of all these reasons leachate control strategies involve the input (waste and water), the reactor (landfill) and the output (leachate and gas).

Control of Waste Input

The first step in the waste input control strategy should be that of reducing to a minimum the amount of waste to be landfilled. This could be obtained by separate collection activities, recycling centres, incineration and composting. Separation of the hazardous fraction of municipal waste such as batteries, expired medicines, paint, mercury lamps, pesticides, etc., would reduce leachate concentrations of heavy metals, halogenated hydrocarbons and other toxic compounds.

Another step is that of reducing waste to a non-leachability level. This could be achieved for MSW by incineration followed by fixation of the solid residues.

Pretreatment could also aim to reduce the biodegradability of waste to be landfilled. This would reduce or even eliminate the need for process water in the biostabilization. One way of reaching this aim is to pretreat waste by mechanically sorting organic matter and paper. This material could then be either composted or anaerobically digested.

Control of Water Input

The strategy for water input control is strictly related to the quality of waste to be landfilled. In the case of non-biodegradable waste, according to its hazardous potential for the environment, prevention of water infiltration can be adopted as the main option (normally by means of top sealing). On the contrary, in the case of biodegradable waste, a water input must be assured until a reasonable degree of biostabilization is achieved. In this case the water input should be limited to the strictly necessary amount and minimization techniques should be applied. The most important parameters in this regard are:

- siting of landfill in low precipitation areas, if possible;
- usage of cover and topsoil systems suitable for vital vegetation and biomass production;

- vegetation of the topsoil with species which optimize the evapotranspiration effect;
- surface lining in critical hydrological conditions;
- limitation on sludge disposal;
- surface water drainage and diversion;
- high compaction of the refuse in place;
- measures to prevent risks of cracking owing to differential settlement.

Furthermore, utilization of mobile roofs on the front of the waste deposit could represent a further useful minimization technique.

Control of Landfill Reactor

The main option in controlling leachate quality through controlling the landfill reactor is the enhancement of the biochemical processes (when biodegradable wastes are deposited).

One of the main objectives is to convert and transport as much carbon as possible from the solid phase into the gas phase rather than into the liquid phase. This is achieved by accelerating the methane generation step.

Control of Leachate Discharge into the Environment

As mentioned earlier, this is the parameter traditionally controlled and nowadays the regulations are more restrictive. The following tools are adopted.

Lining. The lining system should be based on the multi-barrier effect (double or triple liners). Quality of material and construction methods should be improved to ensure higher safety and durability.

Drainage and collection systems. A rational drainage and collection system is important to avoid emission or accumulation of leachate inside the landfill. Unfortunately the level of engineering and operation of drainage systems appears to be very poor and represents one of the shortcomings in current landfill design. The main problems are proper choice of material, clogging, durability and maintenance. No drainage system currently in use appears to be safe enough or long lasting.

Treatment. Leachate has always been considered a problematic wastewater from the point of view of treatment as it is highly polluted and the quality and quantity are modified with time in the same landfill. Nowadays according to the increasingly restrictive limits for wastewater discharge, complicated and costly treatment facilities are imposed. Normally a combination of different processes is required.

Environmental monitoring. This aspect is of extreme importance for the evaluation of landfill operational efficiency and for the observation of the environmental effects on a long term basis.

ISSUES IN THIS BOOK

The aspects of leachate production and composition (including water balances, characterization methods and factors controlling composition), leachate treatment (individual processes, combination of processes, and recirculation) and environmental issues of leachate (fate of pollutants, monitoring) are described in this book following the introduction given in the paragraphs below, whilst lining and leachate collection are described in a following book.

Leachate Production

In most climates rain and snowfall will cause infiltration of water into the landfilled waste and, after saturation of the waste, generation of leachate. Determination of the amount of water infiltrating a covered landfill cell can be made from the hydrological balance of the top cover, paying attention to precipitation, surface run-off, evapotranspiration and changes in moisture content of the soil cover. However, the balancing must be timewise discretized in order to identify the periods of excessive water leading to infiltration into the waste below.

The water content of the waste being landfilled is usually below saturation (actually field capacity) and will result in absorption of infiltrating water before drainage in terms of leachate is generated. The water absorption capacity of the landfilled waste and its water retention characteristics are very difficult to specify due to the heterogeneity of the waste. Furthermore these characteristics may change over time as the waste density is increasing and the organic fraction which dominates the water retention is degraded in the landfill. It has often been observed that new landfills produce leachate soon after the waste has been filled in, although the total water absorption capacity should not be depleted that quickly. Accounting for these aspects is still very rudimentary and definitely the less developed component of the hydrological cycle of the landfill.

Mathematical models for landfill hydrology are currently being developed (e.g. Chapter 2.1) and may prove to be efficient tools in designing leachate-minimizing top covers and determining expected leachate flow rates to be treated before discharge. It should be emphasized also that landfills in areas with an annual deficit of rainfall may produce leachate in the wet season as shown in Chapter 2.2.

Besides improvement of top covers to store moisture for the dry season, establishing short-rotation tree plantations on landfill sections and irrigation with leachate may also prove—even in relatively cold climates—an effective means of reducing the leachate generation rate. Chapter 2.3 describes some extensive Finnish experiments where willow plantations, even in shallow soil covers, increased the evapotranspiration by 400 mm per year, supposedly sufficient to reduce leachate generation substantially in many countries.

Leachate Composition

The characteristics of landfill leachate, as described in Chapter 2.4, are relatively well known, at least for the first 20 years' life of the landfill, the period from which actual data are available. On the other hand the leachate composition of later phases of the landfill is hardly known and the basis for making good estimates is rather weak. However, there is no doubt that for some components the leaching will continue for more than a century.

Leachate from landfills contains a vast number of specific compounds, in particular specific organic compounds in micro-amounts which may make it an impossible task analytically to determine all relevant compounds. As a consequence of this, combined with the uncertainty of the biological effects of mixtures containing many chemicals, biological characterization methods are now beginning to be applied to landfill leachate samples. Ecotoxicological tests (e.g. Micro-tox test and *Daphnia* test) and mutagenic tests (e.g. Ames test) have been applied as described in Chapter 2.5. The results are still too few to make general conclusions on the applicability and reliability of biological characterization methods, but the approach is interesting and further data are expected in the years to come.

Before selection of proper treatment processes for landfill leachate, data on the composition of the leachate in question must be available. Usually chemical data are available making up the basis for treatment design. However, in France a specific procedure, as described in Chapter 2.6, has been applied for characterizing leachate treatability. In addition to traditional chemical analysis this procedure involves gel permeation chromatography. In France this procedure has been applied to the design of several full-scale leachate treatment plants.

Most of our current knowledge on leachate composition originates from landfills that are less engineered and managed than the modern sanitary landfills. New developments identifying the influence of various management procedures on landfill stabilization and hence on leachate composition, as reviewed in Chapter 2.7, show that specific procedures for the landfill operation, and maybe controlled leachate recirculation, may lead to a rapid stabilization of the landfill and to a less polluted leachate. These procedures are expected to gain increasing practical attention in the future.

Co-disposal of hazardous waste in landfills is seen in some countries, based on experiences from old-fashioned landfills and dumps, as malpractice while other countries see co-disposal as an efficient and cheap disposal method for hazardous waste if properly engineered. This means that the type and amount of industrial waste disposed at the landfill must not significantly disturb the degradation processes and negatively influence the quality of gas and leachate. Chapter 2.8 provides a comprehensive report on how the effects of co-disposal can be investigated showing data for both organic and metallic wastes. Our knowledge about engineered co-disposal systems is mostly related to biologically active landfill environments. For compounds that are not degraded but attenuated in the landfilled waste by ion exchange, sorption and precipitation, our knowledge about the long-term effects is still rather scarce.

Characterization of landfill leachate by chemical-analytical methods has during the last 20 years to a large extent developed from standard methods for wastewater characterization. However, leachate differs analytically in many ways from wastewater and the chemical-analytical methods must be adjusted to account for this. No standard methods for leachate analysis exist and much reported data may be based on 'local' adjustments of available analytical procedures. Unfortunately, the methods employed are rarely reported and the transfer of experience is very limited. Chapter 2.9 gives an introduction to various analytical characterization methods emphasizing the special aspects of leachate analysis as compared to wastewater analysis.

Leachate Treatment

Since more and more landfills all over the world will be sealed at their bases by means of mineral and/or artificial liners and leachate will be collected, there is a great need for appropriate leachate treatment facilities. The high concentrations of organic and inorganic constituents in leachate have to be treated due to the requirements in different countries. The tendency is for relatively low effluent concentrations in organics, ammonia, halogenated hydrocarbons, heavy metals, and fish toxicity (see Chapter 3.15). There is still discussion as to whether it makes sense to treat leachate down to low COD-values where at concentrations $\leqq 1000$ mg/litre probably mainly humic- and fulvic-like acids are removed. The potential effects of these components in rivers, lakes, etc., cannot be predicted. Investigations are underway where the organic concentrations of the biologically treated leachate are compared with humic sunstances produced in the natural biological cycle (e.g. humic substances in the forest soils). Hopefully there will be answers in the future.

The removal of nitrogen especially from leachate from the methanogenic phase (low BOD_5- and high COD-concentrations) is still a problem. Nitrification can be achieved when the treatment plants are designed for this purpose. Denitrification can be practised with 'young' leachates; 'old' leachates do not have enough degradable organics to supply denitrifying bacteria with the carbon needed for the reduction of nitrate.

The trace organics have to be looked at in more detail. Also in MSW-landfills halogenated hydrocarbons and other organics like aromatic compounds are landfilled with the daily life products. These components can be found in leachate also and have to be removed by means of special treatment.

Due to the kind of treatment there will still remain a variety of components in the leachate; these will be mainly salts, organic trace components, heavy metals and the above-mentioned humic- and fulvic-like acids.

Leachate treatment plants will consist in the future of more than one step. It may start in the landfill by practising the enhanced biological degradation which results from the early stage of landfilling in low BOD_5-concentrations. The removal of organics and nitrification will mainly take place by means of biological processes while further treatment requires chemical/physical methods.

Leachate treatment will be very costly in the future especially if the required effluent standards of Germany have to be met. There is not much experience in full-scale regarding this new generation of leachate treatment plants. Costs in the range of 30–70 US$ per m^3 are expected that will increase the costs for landfilling substantially. This is especially true when the total time of leachate treatment after the landfill has been closed (50–100 years or more?) is respected.

Concerning the different approaches in the different countries, it has to be kept in mind that legislation, landfill management, operation, etc., may be different. In addition it should be pointed out that there is not only one solution for the treatment of leachate to obtain the required final concentrations. One conclusion from the papers in Part 3 on leachate treatment is the need for leachate minimization procedures.

Biological leachate treatment. About eight papers in Chapter 3 deal with biological treatment procedures for leachate. In general it can be stated that biological leachate treatment is a most favourable procedure that should be used also in those cases when chemical/physical treatment is required. Biological leachate treatment is a relatively low cost process and organics are degraded mainly to CO_2, water, and biomass. All the substances that have been eliminated using biological degradation do not have to be treated by means of high cost chemical/physical procedures.

As already mentioned, with increasing landfill age or by means of enhancement techniques, leachate treatment will mainly focus on the nitrification of ammonia. Biological denitrification can be achieved when an external organic substrate is added to the leachate.

The design criteria for sewage treatment plants cannot be used for leachate. For the design and operation of biological leachate treatment plants specific points have to be respected:

- foam production during certain periods;
- precipitation of constituents that results in clogging of pipes, etc.;
- low leachate temperatures during biological treatment due to long detention times in the reactors;

- low phosphorus concentrations in the leachate;
- low BOD_5 and high ammonia concentrations in old leachate;
- halogenated hydrocarbons.

No investigations have been made so far to determine the stripping effects on volatile organics during aeration.

Co-treatment of leachate and sewage is the treatment process used in most cases. It may operate well if the relation between the amount of leachate and sewage is acceptable (see Chapter 3.14). The final comparatively high COD-concentrations from the leachate will increase the total COD-effluent concentration of the sewage/leachate mixture according to its initial ratio. The AOX-concentrations (chlorinated hydrocarbons) are in general not degraded and may be stripped, adsorbed to the sludge or only diluted.

Chemical–physical leachate treatment. Chemical–physical treatment mainly results in the separation and concentration of pollutants from the leachate. The concentrate has to be incinerated, landfilled, or further treated. So it is not a 'real' treatment process compared to biological methods. Other chemical processes such as wet-oxidation as well as ozone, UV, and H_2O_2 treatment may also result in a conversion of organics to mainly CO_2 and water. In Germany at present ozone- and UV-oxidation processes are being tested at semi-technical scale.

The oxidation processes are expected to improve the biological treatment of the organics and/or to totally oxidize them. By means of reverse osmosis, organic and inorganic components of the leachate are accumulated in the concentrate due to their chemical/physical characteristics. Evaporation or incineration of leachate also remove organics and inorganics from the liquid phase. Precipitation using organic and/or inorganic flocculants mainly results in a removal of organics and an increase of the salt content when inorganic flocculants are used. Activated carbon mainly removes organics from the water and gas phase.

When considering chemical/physical treatment the whole process including energy requirement, gas treatment, residue-removal, quality of the treated leachate, stability and efficiency of the process as well as costs have to be respected.

Leachate recirculation. No detailed research on the effect of leachate recirculation on the water budget of a landfill has been performed so far. Leachate recirculation has been practised in the past in many cases, with the aim of totally solving the leachate problem. Experiences show that under middle European climatic conditions this is not possible and that on the contrary a build-up of leachate in the landfill has been observed. In some cases water migrated over the edge of the landfill pit.

Leachate recirculation may be practised only with biologically treated leachate in a controlled way. The main aim of leachate recirculation is the maximization of evaporation. So leachate recirculation should be practised dependent upon the actual evaporation rate over the year; since this procedure is somewhat theoretical the rate of leachate recirculated with time may be related to the average evaporation rates and the water retention potential in the upper 10 cm of waste and/or cover-soil. A certain amount of leachate may penetrate into the landfill, which in general will not cause adverse effects.

Environmental Aspects of Leachate

The main environmental aspects of landfill leachate are the impacts on surface water quality and groundwater quality if leachate is discharging into these water bodies. In addition nuisance may arise from leachate handling and treatment, e.g. in terms of malodours and aerosols, but these aspects are only temporary and very local.

The effects of leachate on surface waters, e.g. streams and creeks, and groundwater have been recognized for many years. Many cases of leachate impact on surface water and groundwater quality may be linked to improper or insufficient landfill technology of the past, e.g. with respect to either lining or drainage collection. These cases demonstrate that leachate control is a compulsory element of the modern sanitary landfill. In fact the need to control leachate in order to avoid uncontrolled discharges into the environment is bearing the greatest influence on landfill siting, design, operation, maintenance and costs.

An efficient and well managed modern landfill should not cause any uncontrolled releases of leachate into the environment, but it seems important to understand the potential environmental aspects of leachate in order to further develop landfill technology regarding these aspects, to form a basis for risk and environmental impact assessment at new landfills, and to take remedial action efficiently if a leachate release has occurred accidentally.

The main question raised with respect to landfill leachate is the length of time that leachate may constitute an environmental risk. No definite answer is currently available but it seems that we are speaking of hundreds of years rather than decades for the most persistent pollutants. Chapter 4.1 presents a Swiss approach to assessing the long-term influence of leachate from landfills indicating that dissolved carbon may constitute a problem for more than a thousand years. This is a rather long time frame in view of our current experiences with the reliability of constructions. Such realizations may also lead to new discussions on what kind of waste is suitable for landfilling.

Leachate entering the soil and groundwater environments will be subject to attenuation processes such as dilution, biological degradation and physico-chemical processes. The balance between these processes and the leachate load and composition will determine the extent of the leachate plume and the significance of the environmental risks to surface water ecology and to public health through water supplies based on surface water or groundwater. Chapter 4.2 discusses these attenuation mechanisms. Although our understanding of these mechanisms has improved, much still remains to be learned before an integrated understanding of these complex processes is available and predictive methods are developed.

Specific organic compounds in landfill leachate are supposedly the contaminants of most concern in addressing the impacts on groundwater. These specific organics will be present in nearly all landfills originating from household chemicals, small industries and maybe as co-disposed hazardous waste. Chapter 4.3 discusses our current knowledge about the degradation of these compounds in landfill leachate-polluted groundwater. It appears that the redox sequence supposedly present in the leachate plume, ranging from methanogenic conditions close to the landfill to potentially aerobic conditions in the most diluted part of the plume, may be advantageous to the degradation of a range of specific organic compounds. However, we also need to identify the specific compounds that will persist while passing through this sequence. These compounds may appear to possess the major environmental risk.

In licensing landfills, groundwater control monitoring is often demanded by the authorities in order to demonstrate that all the measures taken to prevent contamination of groundwater meet expectations. In order to constitute reliable control monitoring systems many aspects must be taken into consideration, as shown in Chapter 4.4. It is very simple to establish a control monitoring system that will never show an accidental pollution of the groundwater. If not properly designed and operated the groundwater control monitoring system may be an expensive system not providing the intended control and may be insensitive to a contaminant plume that later may appear to be very costly to remedy.

2. LEACHATE PRODUCTION AND COMPOSITION

2.1 Model Prediction of Landfill Leachate Production

NICK C. BLAKEY

Water Research Centre plc, Medmenham, PO Box 16, Marlow,
Bucks, UK, SL7 2HD

INTRODUCTION

Existing and anticipated regulations related to the landfill disposal of wastes and environmental protection indicate that in future an increasing number of landfills will be designed and operated as containment sites. An inevitable consequence will be that greater attention will be paid both to waste management methods which control the volume of leachate produced and to the disposal routes for the accumulated leachate. In order to test the effects of alternative waste disposal schemes on the timing and the volume variations with time of leachate production, a predictive model has been developed which takes account of variables such as changes in the rate of waste input, compaction, cell geometry, surface slopes, influence of intermediate and final covers and changes in liquid inputs. The same data are also a prerequisite to designing rational leachate treatment and disposal options. The volume of leachate and the length of time over which it is produced strongly influence the sizing of treatment plants and, hence, their capital and running costs, as well as potential charges associated with options such as direct disposal to sewer.

At present, the predictive model deals only with leachate volumes. Leachate strengths are estimated empirically, with predictions based on accumulated information on typical leachate compositions (Robinson & Maris, 1979; Department of the Environment, 1986). Nevertheless, a combination of application of the model with knowledge of the characteristics of the various site operational and leachate treatment options allows rational design of leachate control and management systems.

WATER BALANCE

Predictions of the volume of leachate which can be generated from domestic wastes have been variously described (Department of the Environment, 1978; Blakey, 1982; Campbell, 1982; Ehrig, 1983; Holmes, 1984; Lu, 1985; Canziani & Cossu, 1989). Although the approaches employed in these methods vary, they are basically derived from a water balance or budget principle, the principal factors that control leachate production being:

- the monthly balance between the components of liquid input to the site that give rise to infiltration through the surface; and
- changes in the moisture retention and transmission characteristics of the waste as infiltration percolates through successive layers.

For a given area of landfill this can be represented by the following simplified equation employing the terminology of Canziani & Cossu (1989)

$$L = P - R - \Delta U_s - ET - \Delta U_w \qquad (1)$$

where

L = leachate production
P = precipitation
R = surface run-off
ΔU_s = change in soil moisture storage
ET = actual evaporative losses from the bare-soil/evapotranspiration losses from a vegetated surface
ΔU_w = change in moisture content of the refuse components.

Infiltration of liquid into the landfill and absorption of percolating water by wastes are discussed in detail below.

INFILTRATION

The amount of water available for infiltration depends on the relationship between precipitation (P), surface water run-off (R), soil moisture storage (U_s) and actual evaporation/evapotranspiration (ET) as shown in eqn (1).

Daily values of rainfall and calculated estimates of potential evapotranspiration can be derived from Meteorological Office data. Surface water run-off on the other hand is estimated less reliably by using a coefficient appropriate for the surface cover characteristics of the site (slope and type of cover material) (Chow, 1964)

$$R = C \,.\, P \tag{2}$$

where

R = surface run-off peak discharge (mm)
C = run-off coefficient
P = uniform rate of rainfall intensity (mm).

The literature contains many reports of standard run-off coefficients for various agricultural and engineering applications. Table 1 lists three separate examples of run-off coefficients based on individual effects of topography, soil type and surface vegetation. The simplistic approach adopted in the generation of data presented in Table 1 implies that the relationship between run-off and rainfall duration (i.e. (1) short showers only result in wetting of soil surface and filling of depression ponds on the surface and (2) the infiltration rate decreases as the cover material becomes wetter) has not been considered along with the effect of varying the cover material compaction. Although research is currently being funded by the UK Department of the Environment (DoE) into aspects of surface run-off and infiltration through clay-capped landfills, few data are presently available to challenge the validity of this alternative data.

Close examination of the data in Table 1 shows that these estimations are not consistent and data from further investigations of landfill site surface run-off factors are keenly awaited if rational estimation methods are to be used with reasonable accuracy. Despite these reservations, the simplicity of this empirical approach has made it a practical tool used widely by hydrologists and landfill site engineers alike.

The monthly change in soil moisture storage and the effect this has on the potential evaporation can be assessed in the UK by using the Meteorological Office's Rainfall and Evaporation Calculation System—MORECS (Meteorological Office, 1981). Holmes (1984) demonstrated the use of this system for a landfill application and showed that an assessment of soil moisture storage is important in any water balance

TABLE 1. Comparison of Run-off Coefficients for Drainage Areas with Different Topography, Soil, and Cover Conditions

Area type	*Run-off coefficient C*								
	Flat: slope <2%			*'Rolling': slope 2–10%*			*Hilly: slope >10%*		
Bare earth (clay)	0·60	0·60	0·60	0·66	0·70	0·70	0·70	0·82	0·80
(Clay or silt loam)	—	0·50	0·50	—	0·60	0·60	—	0·72	0·70
Meadows and pasture (Clay or silt loam)	0·25	0·30	0·35	0·30	0·36	0·45	0·35	0·42	0·55
Cultivated—impermeable (clay)	0·50	0·40	0·50	0·55	0·55	0·60	0·60	0·60	0·70
Cultivated/permeable (sandy loam)	0·25	0·10	0·20	0·30	0·16	0·30	0·35	0·22	0·40
Reference[a]	1	2	3	1	2	3	1	2	3

[a] 1. Perry, R. H. (1976). *Engineering Manual*, 3rd edn. McGraw-Hill Book Co., New York, 946 pp.
2. Salvato, J. A. *et al.* (1971). Sanitary landfill leaching prevention and control. *JWPCF*, **46,** 2084–2100.
3. Bernard, M. (1982). Discussion of run-off: Rational run-off formulas. *Trans. Am. Soc. Civil Eng.*, **96**.

calculation since this determines the amount of liquid percolation through the cover soil into the refuse layers beneath.

On a restored site, infiltration through the cover soil can be limited further by plant growth. The amount of water retained by plants is only a small fraction of the total absorbed by the roots. By far the greater part is transported to the aerial parts of plants where it evaporates into the surrounding air. Given an abundant supply of moisture in the soil then the loss of water as vapour from plants is controlled by the prevailing climatic conditions and is termed the potential evapotranspiration. There are two states of water in the soil available to plants; the first is gravitational water which temporarily displaces air from large spaces between the soil particles following rain and gradually percolates downwards under the influence of gravity. The second is capillary water which comprises the bulk of the water remaining in the soil after gravitational water has drained away, and is the main source of water to plants. Soil containing the maximum amount of capillary water and no gravitational water is said to be at its field capacity. When the soil dries and is no longer at field capacity then evaporation is less than the potential rate and a soil moisture deficit will develop.

Where identified in the computer model, this deficit is decreased by subsequent monthly rainfall until it becomes negative. At this point excess rainfall passes through the soil cover and is considered to be hydrologically effective. Estimating infiltration in this way can lead to a high degree of variability in effective rainfall from year to year even though the annual average rainfall levels remain similar. In other words a high proportion of rainfall falling in the low potential evapotranspiration months during the winter will produce greater amounts of effective rainfall compared to a year with a more even rainfall distribution.

An illustration of the relationship between rainfall and calculated infiltration is provided by data generated from a number of experimental landfills sited at Edmonton, North London (surface area of each experimental landfill, 90 m^2). The variation in annual rainfall exceeded 50 percent during the five-year period of investigation (Table 2). Of particular interest is that rainfall during year 3 was 15 percent greater than the two preceding years and yet the calculated infiltration was shown to be less. This was due to heavy rainfall events during the summer months where evapotranspiration was maximised.

These infiltration levels are not atypical for the operational phase of a landfill where surface water run-off is minimal. Values in excess of 50% have been recorded with seasonal variations ranging from 20 to 70% in the

TABLE 2. Annual Rainfall and Calculated Infiltration from Experimental Landfills, Edmonton, North London[a]

Year	*Rainfall*[b] *(P) (mm)*	*Calculated infiltration* (P_i)	P_i/P *(%)*
1	532	219	41
2	594	255	43
3	685	266	39
4	808	403	50
5	531	222	42

[a] Data on the experimental landfills appear in Table 3.

[b] Average data collected from four Meteorological Office stations within 4 km of the site.

summer and winter, respectively (Campbell, 1982). Ehrig (1983) has shown that values in the range 35–80% have also been recorded at operational sites in Germany.

Typical values of infiltration through cover soils at restored landfills have been shown to range between 14 and 34% of annual rainfall (Holmes, 1984). These levels may be reduced further by installing sub-surface drainage systems or by encouraging surface water run-off by surface contouring.

It is very clear from these observations that gross estimation figures quoted as national or regional guidelines should be avoided where more precise estimation of infiltration is required. It is recommended that careful assessment of the interaction of rainfall and site surface conditions be carried out bearing due regard for the differences in climatic conditions that may prevail in the vicinity of the landfill site (e.g. differences between conditions at the bottom of a deep quarry compared to the surface).

ABSORPTION

In order to clarify the terminology used to describe the assumed moisture-related properties of domestic waste a number of definitions are given below:

- Initial moisture content of domestic waste is the moisture that waste contains when first received at the site for disposal.

Although subject to waste type, seasonal trends and treatment after collection (i.e. wet pulverisation, baling, or mixing with other wastes under co-disposal conditions), a typical value of 35 percent of dry weight (equivalent to 26 percent of wet weight) is often quoted.

- Field capacity is often used to quantify the amount of liquid that a given mass of material will absorb before downward percolation occurs due to gravitational forces. This definition is suitable for homogeneous materials such as soils and perhaps pulverised domestic waste. However, with crude domestic wastes, liquid is released before field capacity is reached. For this reason, it is more meaningful to rename this term the 'absorptive capacity' of the domestic waste, indicating the point at which leachate will first be generated.
- Saturation capacity of the waste is reached over a period of years after the absorptive capacity is achieved. This is the amount of liquid that is retained within the void in which the waste is deposited.

These definitions imply two major and well recognised mechanisms for moisture retention within domestic wastes:

- physical absorption of liquid within the landfill which is determined by capillary forces;
- apparent absorption of water within void spaces in the waste giving localised areas of saturation.

Several factors are known to affect the first of these mechanisms, the absorptive capacity:

- Waste density. At waste densities commonly achieved in the UK ($0{\cdot}7$–$0{\cdot}8\ \text{t/m}^3$) absorptive capacities of $0{\cdot}16$–$0{\cdot}27\ \text{m}^3$ per dry tonne have been reported (Department of the Environment, 1978; Blakey, 1982). However, work has shown that where emplacement densities approach $1\ \text{t/m}^3$, absorptive capacities may fall to as little as $0{\cdot}02$–$0{\cdot}03\ \text{m}^3$ per dry tonne (Campbell, 1982).
- Short-circuiting of liquid through waste (preferential pathways) can be established within a body of waste which is not highly compacted, through which infiltrating liquid may pass rapidly without being absorbed.
- Rainfall intensity. The effect of a high rainfall event would be to encourage short-circuiting.

Additionally, research has shown that where landfilled wastes have received prolonged periods of infiltration the additional uptake of liquid, over and above an average value of 35% of dry weight for the initial moisture content of domestic waste, is of the order 0·40–0·65 m^3 per dry tonne of waste (Blakey, 1982). Although it can be argued that at least a proportion of this moisture might eventually drain from the wastes under gravity it is an important factor to be taken into account in any landfill water balance model.

In order to predict the quantity and pattern of leachate discharge from domestic waste a realistic estimation of the amount of absorption of infiltrating rainfall has been calculated for the experimental landfills at Edmonton, North London, using a site water budget. Here, calculated infiltration has been balanced against measured leachate output; infiltration has been estimated using actual rainfall, evaporation and evapotranspiration data where appropriate and taking into account soil moisture deficit where calculated during the summer months.

For the first six months of operation, leachate production accounted for only 6–10% of the estimated infiltration in cells 1, 2 and 4 (Table 3). This indicated that an initial uptake of liquid of 0·07–0·08 m^3 per dry tonne of waste had occurred (Fig. 1). The comparatively small volumes of leachate produced during this initial period are considered to represent short-circuting of infiltration through the domestic wastes since the major proportion of leachate up to this time had been collected from drainage bunds along the edges of each cell wall. These isolate leachate collected from the main body of the waste from such short-circuiting.

In comparison, up to 25% of measured infiltration was drained from cell 2 over the first six months. This was thought to be due to the abnormally high levels of putrescible waste which had dramatically increased the moisture content of the wastes held in this cell (Table 3).

After 12 months when the quantity of leachate, as a percentage of infiltration, continued to rise the amount of liquid resident within the cells also increased, particularly in response to heavy rainfall. This decreased only slightly during periods when little infiltration took place (Fig. 1). This increase in apparent liquid absorption was not observed in cell 2 where liquid storage in excess of initial moisture content fluctuated about a mean of 0·07 m^3 per dry tonne.

The apparent discrepancy in liquid storage between the cells indicated in Fig. 1 can be clearly attributed to the initial moisture content of the wastes as emplaced, and in particular the influence of the moisture held in the industrial or putrescible wastes. For example, the phenol lime

TABLE 3. Details of Cell Contents and Water Balance for Four Experimental Landfills at Edmonton, North London (July 1979—May 1984)

Cell	1						2						3						4					
Contents																								
1. Domestic waste (tonnes-dry wt)	126·2						100 (143 from April 81)						98·1						96·3					
2. Other waste (tonnes-dry wt)	— (control)						10 (putrescible food waste) (12·1 from April 81)						28·8 (phenol lime mud)						19·1 (spent oxide)					
Period monitored (months)	6	12	24	36	48	59	6	12	24	36	48	58	6	12	24	36	48	58	6	12	24	36	48	59
Calculated infiltration (mm)	114	219	474	740	1 143	1 365	114	219	474	740	1 143	1 434	114	219	474	740	1 143	1 365	114	219	474	740	1 143	1 365
Leachate volume (mm)	7	28	118	271	515	618	29	100	310	632	1 046	1 205	11	61	211	402	670	497	11	61	211	402	670	774
Leachate production as a percentage of estimated infiltration for each period (%)	6	20	35	58	61	46	25	68	82	121	103	79	7	17	41	46	45	28	10	48	59	72	67	47
'Absorption'[a] of moisture (litres/dry kg)	0·07	0·15	0·25	0·32	0·43	0·51	0·07	0·10	0·09	0·06	0·05	0·09	0·07	0·13	0·24	0·34	0·49	0·60	0·08	0·12	0·20	0·26	0·36	0·45

Rainfall was measured on site as well as at four Meteorological Office stations.

[a] Water 'absorbed' is that volume which cannot be accounted for as leachate or evaporation.

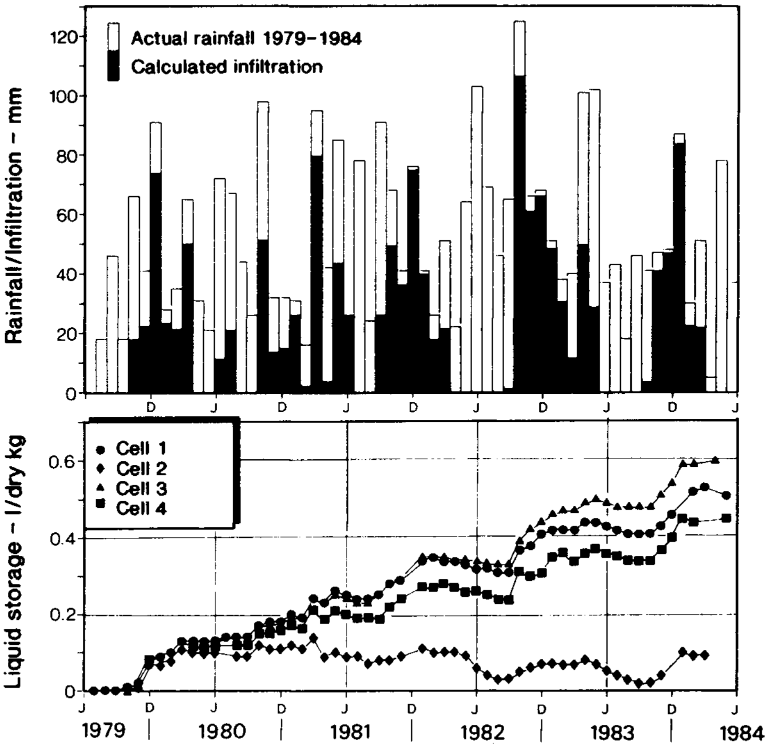

Figure 1. The effect of infiltration on calculated liquid storage of wastes contained in four experimental landfills at Edmonton, N. London. (Cell 1—domestic waste only; Cell 2—domestic/putrescible waste mix; Cell 3—domestic/phenol lime sludge waste mix; Cell 4—domestic/spent oxide waste mix.)

mud contained in cell 3 had a moisture content of 27% of wet weight (Barber *et al.*, 1980) and over the first three and a half years of operation moisture storage in this cell showed no appreciable difference to that of the control cell 1 (Fig. 1). On the other hand, cell 4, containing a spent oxide waste initially holding 49% of wet weight as moisture, showed significant changes in the apparent moisture storage of the wastes. This reduction in the amount of additional uptake of liquid can be compared with cell 2 where the putrescible wastes, containing 80–90% of wet weight as moisture, had a pronounced effect on the apparent moisture storage in the cell (Fig. 1).

These findings show that site operators need to be aware of the potential problems associated with relatively large quantities of waste with high moisture contents. Where these wastes are accepted for disposal, moisture retention within the wastes cannot be exploited during the operational phase of the landfill to delay the production and reduce the volume of leachate.

To illustrate this point further, all the factors so far described have been combined together in the development of a computer model which has been used to predict leachate production from the Edmonton test cells.

COMPUTATIONAL MODEL

The model assumes that once all the refuse in a landfill reaches its saturation capacity an equilibrium is achieved and a uniform leachate generation pattern is obtained. The time taken for leachate to appear is estimated from a moisture movement calculation. The model first calculates infiltration through the cover material or surface of the landfill, and then using these results calculates the rate of vertical movement through the underlying layers of compacted wastes.

The results obtained from the model for the Edmonton test cells are shown in diagrammatic form in Figs 2A and 2B. The widening discrepancy between calculated infiltration and predicted drainage in Fig. 2B represents the steady increase in moisture retention in cells 1, 3 and 4 that was shown in Fig. 1. This effect is absent in cell 2 where the wastes reached saturation capacity relatively rapidly (Fig. 2A and Table 3).

When taking moisture storage fluctuation into account, reasonable agreement between predicted drainage and actual leachate discharge from all four cells has been obtained. For comparison, infiltration and predicted drainage has been estimated using 10-year average data for southern England (Rothamsted, 1960–1969). In this instance predicted drainage bears little relation to actual leachate discharge from the cells. This serves to demonstrate that where realistic estimations of leachate production are to be calculated the importance of using site specific data cannot be overemphasised. Gross estimation figures and national or regional average meteorological data should be avoided wherever possible.

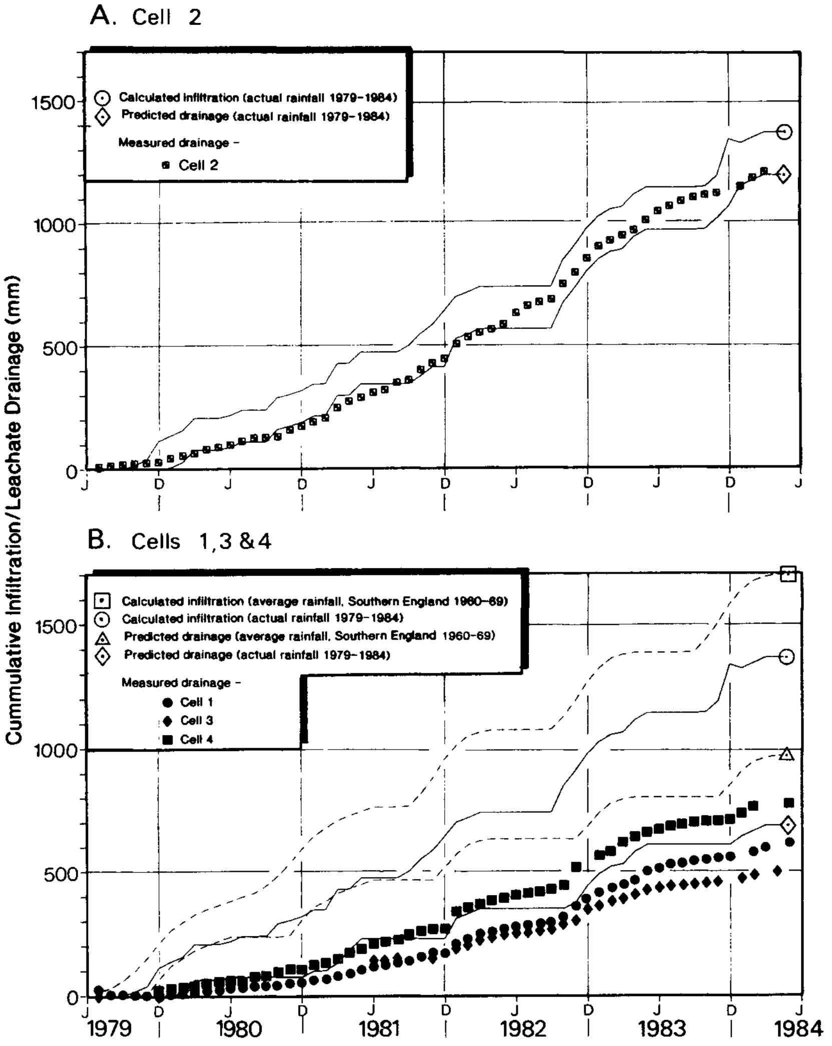

Figure 2. A comparison between the expected pattern of infiltration and leachate drainage with observed flow from four experimental landfills at Edmonton, N. London. (Cell 1—domestic waste only; Cell 2—domestic/putrescible waste mix; Cell 3—domestic/phenol lime sludge mix; Cell 4—domestic/spent oxide waste mix.)

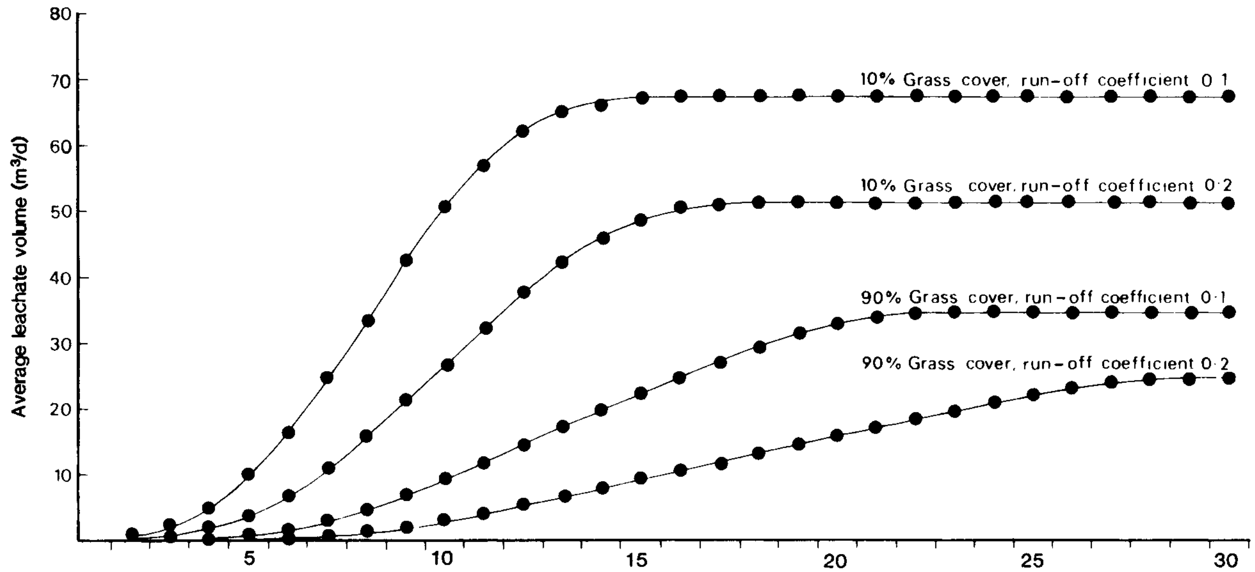

Figure 3. Predicted effects of changes in evapotranspiration and run-off on leachate volume.

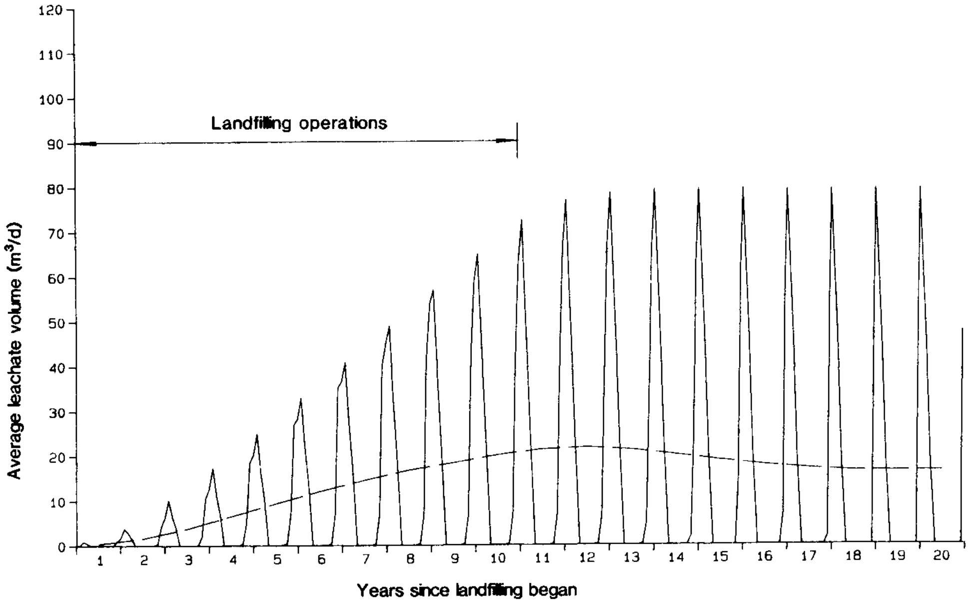

Figure 4. Predicted changes in average daily leachate volume following progressive restoration and grass cover. Monthly basis (full line), annual basis (dotted line). Specific data for landfill: rate of filling = 600 tonnes/week; density of fill = 0·96 tonnes/m^3; precipitation = 750 mm/year; run-off coefficient = 0·1.

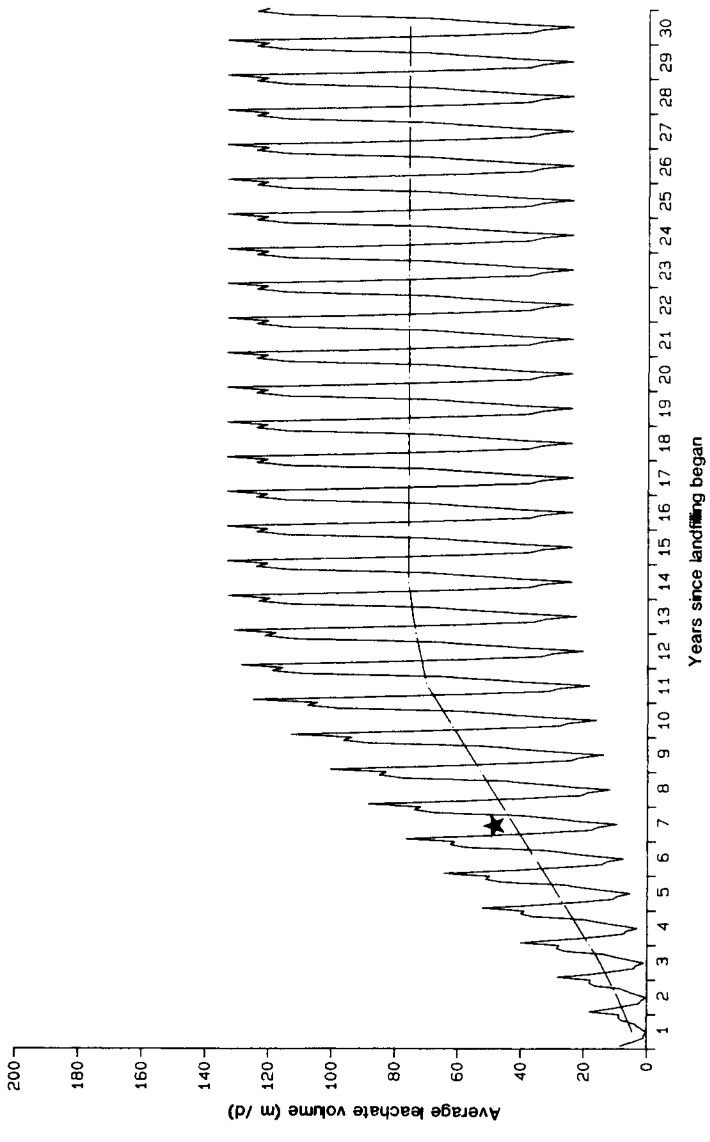

Figure 5. Comparison of predicted and measured leachate from a landfill site: monthly basis (full line), annual basis (dotted line). ★—Actual/measured winter leachate flow, seven years after start of filling. Specific data for landfill: density of fill = 0·8 tonnes/m^3; precipitation = 1620 mm/year; run-off coefficient = 0·4.

In this, its simplest form, the model assesses a fixed surface area and depth of waste as would be the case for a completed landfill. However, the model can also assess leachate production at a working landfill where increasing surface area and variable depth of waste is encountered. This enables a more realistic estimation of the landfill water balance and also gives some insight into those features of the landfill operation which may increase or decrease leachate generation (i.e. surface run-off, progressive restoration, etc.).

Figure 3 shows how sensitive the model is to selection of appropriate run-off and evapotranspiration factors for an 8-hectare lined landfill in southern England. Assuming a weekly waste input of 2500 tonnes and an annual rainfall of about 770 mm, the sharp decrease in predicted flows associated with higher run-off values or increased evapotranspiration (10% grass compared with 90% grass cover) is clearly displayed.

In practice, evapotranspiration losses would be expected to increase with time, as a site is progressively restored and vegetation cover becomes fully established. The effect on leachate flow of such a regime is shown in Fig. 4, which is based on a hypothetical landfill covering an area of 5 hectares, with a waste depth ranging between 5 and 8 metres and a surface slope of 2%.

The effect of high rainfall input on leachate production pattern is well illustrated in the case of a natural containment site of about 6 hectares receiving 650 tonnes of waste per week (Fig. 5), where recorded winter discharges of leachate of about 55 m^3/day in 1986/87 correspond well with predicted values from the model.

CONCLUSIONS

A landfill water balance model has been developed to provide a quantitative assessment of landfill leachate generation. This has been used to estimate leachate production from a series of experimental and full-scale landfills. Despite the limitations of the simplistic approach adopted, the model has been found to be reasonably accurate and is now finding application as a planning tool in waste management.

Infiltration has been shown to be site specific and seasonally variable. The experimental landfills demonstrate that under these circumstances it is inappropriate to use gross estimation models using national or regional figures for rainfall and evaporation/evapotranspiration. It is recommended that careful assessment of the interaction of rainfall and site surface conditions be carried out at least on a monthly basis using site specific data.

Substantial reductions in the level of infiltration can be achieved during the operational phase of the landfill, as well as after restoration, by encouraging surface water run-off. This is particularly important during the winter months when evaporation/evapotranspiration is at its lowest.

At emplacement densities of 0·6–0·8 t/m^3, and with an initial moisture content of 35% of dry weight, it is likely that an absorptive capacity of 0·16–0·27 m^3 per dry tonne of waste can be achieved before substantial leachate generation commences. After prolonged periods of infiltration this absorptive capacity can be exceeded to reach a saturation capacity of 0·4–0·6 m^3 per dry tonne of waste.

Liquid retention and migration characteristics in landfilled wastes and its eventual emergence as leachate have been studied using a variety of waste mixes. Experimental evidence shows that where the initial moisture content of waste is substantially greater than 35% of dry weight then the saturation capacity is reached much more rapidly. Under these circumstances the moisture retention characteristics of the waste cannot be exploited in the same way to delay production and reduce volume of leachate during the operational phase of the landfill.

REFERENCES

Barber, C., Maris, P. J. & Johnson, R. G. (1980). Behaviour of wastes in landfill sites: Study of the leaching of selected industrial wastes in large-scale test cells, Edmonton, N. London. WLR Technical Note No. 69, Department of the Environment, UK.

Blakey, N. C. (1982). Infiltration and absorption of water by domestic wastes in landfills—research carried out by WRC. Harwell Landfill Leachate Symposium, Harwell, Oxon, UK, 19 May 1982.

Campbell, D. J. V. (1982). Absorptive capacity of refuse—Harwell research. Harwell Landfill Leachate Symposium, Harwell, Oxon, UK, 19 May 1982.

Canziani, R. & Cossu, R. (1989). Landfill hydrology and leachate production. In: *Sanitary Landfilling: Process, Technology and Environmental Impact*, ed. Christensen, T. H., Cossu, R. & Stegman, R., Academic Press, London, Chapter 9.1.

Chow, V. T. (Ed.) (1964). *Handbook of Applied Hydrology*. McGraw-Hill, New York.

Department of the Environment. (1978). Co-operative programme of research on the behaviour of hazardous wastes in landfill sites. Final report of the Policy Review Committee (Chairman, J. Sumner). HMSO, London, 1978, 169 pp.

Department of the Environment. (1986). Waste Management Paper No. 26, Landfilling wastes. HMSO, London, 206 pp.

Ehrig, H.-J. (1983). Quality and quantity of sanitary landfill leachate. *Waste Management and Research*, **1,** 53–68.

Holmes, R. (1984). Comparison of different methods of estimating infiltration at a landfill site in South Essex with implications for leachate management and control. *Q. J. Eng. Geol. London*, **17,** 9–18.

Lu, J. C. E. (1985). *Leachate from Municipal Landfills. Production and Management*. Pol. Tech. Review, 119, Noyes Publications, Park Ridge, NJ.

Meteorological Office. (1981). Rainfall and evaporation calculation system—MORECS. *Hydrological Memorandum*, **45,** 27 pp.

Robinson, H. D. & Maris, P. J. (1979). Leachate from domestic waste: generation, composition and treatment. A review. WRC technical report TR 108, WRC, UK, 38 pp.

2.2 Production of Landfill Leachate in Water-Deficient Areas

GEOFFREY E. BLIGHT, DAVID J. HOJEM & JARROD M. BALL

University of the Witwatersrand, PO Wits, 2050,
1 Jan Smuts Avenue, Johannesburg, South Africa

INTRODUCTION

Water is a scarce commodity in arid and semi-arid areas and pollution of surface and underground water resources can be disastrous to communities and households depending on these sources for domestic supply.

As much of the Earth's land surface consists of water-deficient areas, concern has arisen lest existing and future sanitary landfills are causing, or have the potential to cause, unacceptable water pollution. Such pollution is also most costly and difficult to clear up once it has occurred. If nothing is done to ameliorate the situation, the pollution may persist in the groundwater for decades (Ball & Blight, 1986) even though the source of the pollution has been removed.

A preliminary study (Ball & Blight, 1986; Blight *et al.*, 1987) 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 from the base of the landfill. Hence, if there is an adequate separation between the lowest level of refuse and the highest level of the regional phreatic surface, no groundwater pollution will occur. By extension, surface water replenished by the groundwater will also remain unpolluted by leachate from the landfill.

There is considerable support for this view in the literature. For example, Keenan (1986) gives figures indicating that landfills receiving more than 750 mm of precipitation per annum will eventually produce leachate, while those in arid regions receiving less than an annual 325 mm are likely never to exude pollution. Saxton (1983) states that for climates where annual precipitation is less than 400 mm, virtually all precipitation is evapotranspired.

Earlier, Fenn *et al.* (1975), Burns & Karpinski (1980) and Holmes (1980) all agreed that if a net annual water deficit exists at the site of a landfill, little if any leachate will exit from its base.

It must also be recognised that good engineering and management of a landfill can be used to maintain a perennial water deficit within the fill even though there may actually be an excess of precipitation over potential evaporation. This can be done by maximising run-off and minimising infiltration into the refuse. A suitably sloping surface and the installation of a carefully designed impervious cover layer can achieve this (e.g. Lundgren & Elander, 1987).

This chapter describes a recent detailed investigation into the movement and retention of water within two sanitary landfills located in water-deficient areas in South Africa. The results largely corroborate the evidence outlined above and have formed the basis for a set of guidelines for the design of sanitary landfills in water-deficient regions, to avoid water pollution.

THE WATER BALANCE FOR A LANDFILL

The water balance for a landfill can be stated as follows

water input = water output + water retained

In this equation, each term represents a rate of accumulation or loss. Water input includes precipitation (P) and the water content of the incoming waste (U_w). U_w, however, only makes a once-off contribution to the annual water balance of a given mass of landfill. Water output includes evapotranspiration (ET), water vapour entrained by gas (G), water lost in leachate (L), and run-off (R). Finally, there is water absorbed and retained by the waste (ΔU_w) and the soil cover (ΔU_s), i.e. for an annual water balance,

$$P + U_w = ET + G + L + R + \Delta U_w + \Delta U_s \tag{1}$$

In the present study G has been ignored, as it is understood to be small in comparison with the other terms. The annual water balance equation,

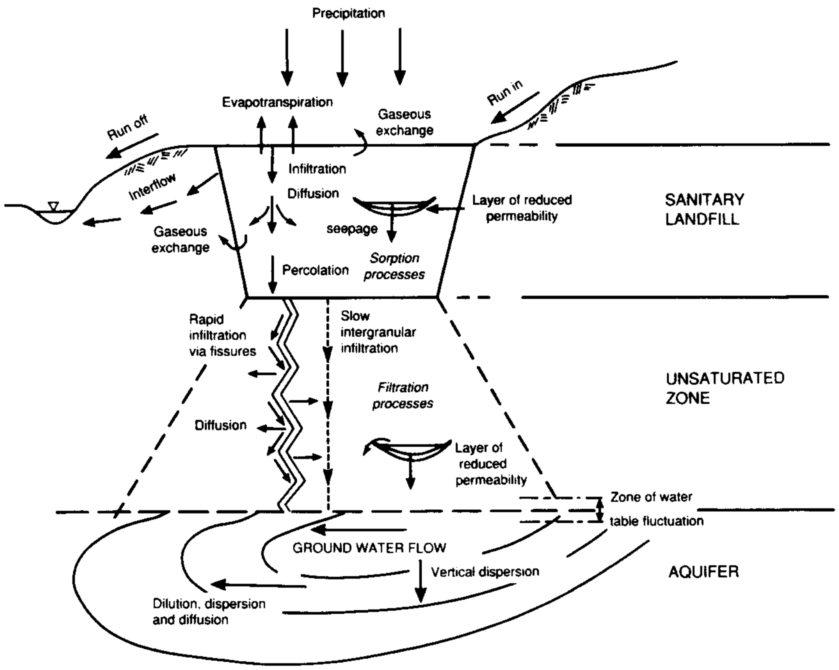

Figure 1. Details of water balance in a sanitary landfill.

as applied to an established landfill, has been simplified to

$$P = ET + L + R + \Delta U_w + \Delta U_s \tag{2}$$

Figure 1 (after Naylor *et al.*, 1978) illustrates the components of the water balance for a landfill in greater detail. In eqn (2), the only components that can be directly controlled by the engineer are the run-off R, and by limiting infiltration, the terms ΔU_w and ΔU_s. In terms of eqn (2) the leachate production L is given by

$$L = P - ET - R - \Delta U_w - \Delta U_s \tag{3}$$

Obviously the smaller the precipitation (P) and the larger the evapotranspiration (ET) and run-off (R), the less the potential for the generation of leachate (L). These terms are particularly favourable in water deficient areas.