A technical assessment of leachate recirculation

Report: SC030144/R6

Better regulation programme

Evidence Directorate

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84911-147-8

Further copies of this report are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506
E: enquiries@environment-agency.gov.uk.

Author(s):
Richard Beaven
Keith Knox
William Powrie

Dissemination Status:
Released to all regions
Publicly available

Keywords:
waste, landfill, leachate, recirculation

Research Contractors:
Waste Management Research Group, School of Civil Engineering and the Environment, University of Southampton

Knox Associates (UK) Ltd

Environment Agency's Project Manager:
Peter Braithwaite, Evidence Directorate

Project Number:
SC030144/R6

Product Code:
SCHO1109BRJC-E-P

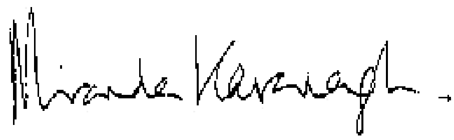
Evidence at the Environment Agency

Evidence underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us, helps us to develop tools and techniques to monitor and manage our environment as efficiently and effectively as possible. It also helps us to understand how the environment is change and to identify what the future pressures may be.

The work of the Environment Agency's Evidence Directorate is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The Research & Innovation programme focuses on four main areas of activity:

- **Setting the agenda**, by informing our evidence-based policies, advisory and regulatory roles;
- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
- **Carrying out research**, either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.



Miranda Kavanagh

Director of Evidence

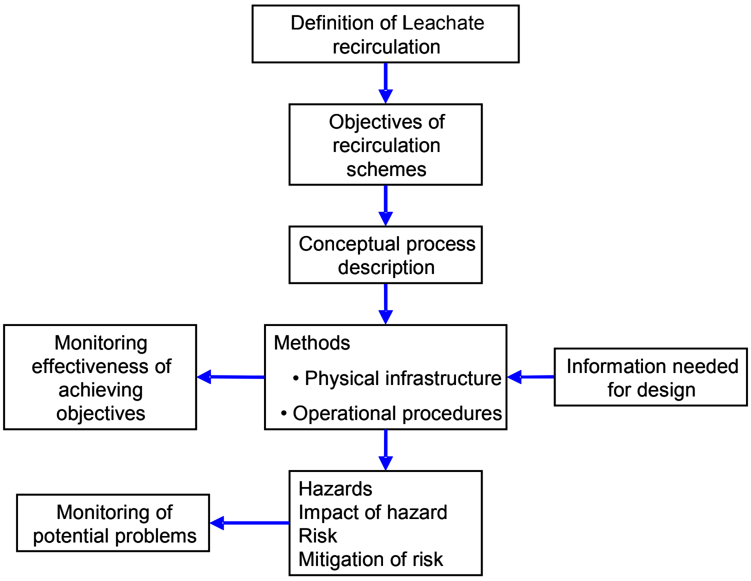
Executive summary

Leachate recirculation within landfills has been in widespread use for a range of purposes since the 1970s. There is currently a particular interest in how it could be used to improve the sustainability of landfill, by accelerating gas production and flushing contaminants from the waste. It is, however, essential that the key technical, environmental and operational issues are properly understood for all applications of leachate recirculation and that the objectives of recirculation in a particular case are clear. Assessment of the benefits and potential risks can be aided by drawing on experience and practice: the Environment Agency therefore commissioned a technical review of leachate recirculation including an investigation of current practice and experience in the UK.

The technical review involved:

- the development of a conceptual framework identifying the key technical, (scientific), environmental and operational (including monitoring) issues associated with leachate recirculation; and
- a review of current UK practice, from both the operators' and regulators' perspectives.

The conceptual framework for evaluation of leachate recirculation that was developed is shown below.



Leachate recirculation is defined in Environment Agency guidance LFTGN03 as: 'the practice of returning leachate to the landfill from which it has been abstracted' (Environment Agency 2004). Within the context of this review, the definition has been expanded to include the introduction of any liquids into a landfill.

There are many possible reasons for undertaking leachate recirculation. They include:

- seeding new basal layers to establish methanogenesis;
- managing leachate quality feed to leachate treatment plants;
- leachate flow management (peak flow buffering/absorptive capacity);
- accelerating settlement/increasing airspace;

- stimulating gas generation;
- accelerating stabilisation of organic waste;
- contaminant flushing;
- fire/elevated temperature control.

The scale and design details of a leachate recirculation scheme will depend on the objectives of the scheme. In most engineering projects, a conceptual process description is developed at an early stage to provide the template for detailed design, construction, operational and control purposes and for deriving cost estimates. Examples are given of how this approach could be applied to leachate recirculation schemes and a strong recommendation is made that such a methodology should be adopted more widely.

The review of UK operators involved six of the major UK waste management companies, and an overview of activities at approximately 90 landfills was provided. There are many reasons why the UK operators are undertaking, or are interested in, leachate recirculation. The most common objectives were seasonal flow balancing of leachate and stimulation of degradation to optimise gas generation and utilisation rates from sites.

A wide range of different leachate recirculation systems have been used, on varying scales and with varying degrees of success. Typical systems include:

- **Low pressure surface application** e.g. bowser/sprinkler bar to irrigate leachate at the tipping face; open trenches or pits in surface of waste; and open-ended pipes laid on waste surface.
- **Systems immediately below top liner** e.g. linear tyre or rubble filled trenches; perforated pipes in a trench filled with drainage material. Some systems were designed to be horizontal and some to include a fall in the trenches.
- **Horizontal linear structures at depth within wastes** (i.e. constructed during infilling) e.g. 'spiders' consisting of horizontal pipes connecting radially to a central access sump/pipe; horizontal pipes or trenches with vertical access points or side slope risers.
- **Subsurface pads of drainage material** (constructed during infilling) e.g. rectangular pads filled with drainage material, often whole or shredded tyres: designs can vary from a 20 x 40 m grid of small 1 x 1 m pads of drainage material with individual access pipes connected to a central well, to single large pads of tyres, the largest being 50 x 50 m x 2 m deep with a vertical access pipe.
- **Subsurface band drains** (constructed during infilling). These are geotextile drainage 'socks' installed by percussion at 1 m centres on a 40 x 40 m grid, to alternating depths of 5, 10 and 15 m. The top surface of the 'socks' is then overlain by a bed of drainage material to distribute injected leachate evenly over the whole area. This is accessed from the surface by a vertical pipe. Infilling with waste then continues over the area.
- **Vertical wells** (e.g. existing leachate abstraction/monitoring wells or gas wells). A few operators have investigated the use of pin wells. These are percussion installed wells approximately 5–10 m deep typically at 20 m centres on 80 x 100 m area.
- **Deep vertical trenches**

To help put the UK's experience into context, information on a number of large-scale and well-instrumented recirculation schemes in other countries was considered. There is reasonably extensive literature available from the USA, where the waste industry and the EPA are actively involved in bioreactor research, and where leachate recirculation is often considered an integral part of operational procedures. Other major research programmes on leachate recirculation have taken place in France and the Netherlands.

The theory of leachate injection is considered both within the context of experiences from the agricultural irrigation sector and also as an unsaturated flow modelling problem. Theoretical and practical design of leachate injection infrastructure is considered.

The report makes a number of observations on operational issues associated with leachate recirculation schemes. These can be summarised as:

Infrastructure design
A wide range of performances were reported, with areal application rates from 1 to 30 m^3/ha/day. Some systems have accommodated very large volumes but it is unclear how long these could be sustained in the long term. The lateral zone of influence of systems, where investigated, was limited to approximately 5 to 15 m, typically <10 m.

Clogging of injection infrastructure
There is little quantitative information on this problem, but clogging of injection infrastructure over a period of just a few weeks appears common when the injected leachate is acetogenic.

Flooding of gas wells
Localised flooding of nearby gas wells was identified as a common consequence of recirculation. Intermittent injection into leachate recirculation infrastructure appears to be the best approach to overcome these problems and is used routinely by several operators interviewed during this study, as well as being referred to in literature.

Effects of settlement
Many operators reported problems with failure of pipe work in horizontal pipes and radials, attributed to settlement. Settlement on most landfills will be significant, and some types of infrastructure may be better able to accommodate settlement (e.g. pads, band drains and surface applications) than others (e.g. some horizontal pipe systems).

Clogging of basal drainage layer
No evidence was found of this resulting from recirculation.

Obtaining sufficient volumes to recirculate
On many sites the amount of leachate recirculated was insufficient for the quantity needed to stimulate gas generation. This was a common theme and is related in part to schemes not being linked to a proper conceptual design where target recirculation volumes would be identified at an early stage.

Slope instability
No instances were reported that were directly attributed to recirculation, but this clearly remains a potential risk.

The report makes a number of observations on environmental issues associated with leachate recirculation schemes. The principal ones are:

Odours, gas release and the potential for air ingress
This was identified as a significant issue during the installation of band drains, due to exposure of waste during the placement of densely spaced bores and may also apply to other types of injection system.

Perching/surface outbreaks
These were commonly observed and may occur due to lateral movement along layers of daily cover, or as a consequence of high pressures caused either by pressure injection or by sub-cap systems being constructed to a fall instead of horizontal.

Adverse impact on leachate quality
There was a common perception that leachate recirculation could lead to deteriorating leachate quality, but there was no evidence to support it. Short-lived flushes of acetogenic leachate may occur at the onset of recirculation.

Increased head on liner systems
There was no evidence that leachate recirculation increases the head on liner systems.

The range of monitoring needed to address the operational and environmental issues above may be separated into four functional groups, namely:

- operational performance of recirculation infrastructure;
- effects on waste decomposition and leachate quality;
- water balance and volumetric aspects;
- environmental risk aspects.

Proposals are made for possible monitoring functions. The exact requirements and frequency of monitoring will depend on the site, objectives and scale of the scheme.

Greater attention must be paid to the conceptual design to meet the objectives of recirculation and to monitoring the operation. Leachate recirculation should be incorporated in operators' leachate management plans. The review has developed an overall evaluation framework, a checklist for evaluating schemes and initial suggestions for the monitoring that may be appropriate. It must be emphasised that these should be applied in a way that is proportionate and necessary for individual proposals.

Acknowledgements

We are very grateful to all the individuals we contacted from the various landfill companies, for their constructive and enthusiastic responses to our survey.

Contents

1 Introduction

Leachate recirculation has been in widespread use for a range of purposes since the 1970s. There is currently a particular interest in how it could be used to improve the sustainability of landfill, by accelerating gas production and flushing contaminants from the waste. It is, however, essential that the key technical, environmental and operational issues are properly understood for all applications of leachate recirculation and that the objectives of recirculation in a particular case are clear. Assessment of the benefits and potential risks can be aided by drawing on experience and practice: the Environment Agency has therefore commissioned a technical review of leachate recirculation including an investigation of current practice and experience in the UK. The study has been undertaken by the University of Southampton and Knox Associates under Science Contract SC030144.

The technical review has been undertaken as an independent assessment and is not intended to reflect the Environment Agency's views or its regulatory position on recirculation.

1.1 Objectives

The objectives of the work were to provide a technical review of the issues involved in leachate recirculation, and to suggest a framework for evaluating and monitoring proposed leachate recirculation schemes.

1.2 Programme of work

The programme of work was as follows.

Task 1 – Development of a conceptual framework identifying the key technical, (scientific), environmental and operational (including monitoring) issues associated with leachate recirculation.

The framework was intended to be used for two main purposes:

- as a template in this study for identifying important topics: information on these topics was obtained from the literature and formed the basis of questions aimed at operators in Task 2a (see below);
- to form the basis of a checklist that the regulator can use when assessing proposals from operators to undertake leachate recirculation.

Task 2 – Review of current UK practice

2a – Operators' experience: A high level review of current leachate recirculation practice in the UK was undertaken by consulting a number of major landfill operators.

2b – Regulators' experience: A one-day informal discussion group was held with Environment Agency staff to discuss the framework and regulators' experience of the performance of current schemes.

Task 3 – Preparation of final report

The final report was prepared by combining information from Tasks 1 and 2, and is structured as follows:

- Chapter 2 sets the study in *context*. It indicates the wide range of possible objectives of recirculation, provides a framework for evaluating individual recirculation proposals, and gives examples of conceptual process descriptions for different objectives.
- Chapter 3 summarises recirculation *infrastructures* used to date by UK operators, classifying them into seven broad categories.
- Chapter 4 describes some of the most significant *studies undertaken outside the UK*, and the most relevant findings from them.
- Chapter 5 presents some *design considerations*, including parallels with agricultural irrigation, the consideration of unsaturated flow theory as applied to leachate recirculation, and flow modelling of leachate injection infrastructure.
- Chapter 6 summarises operators' experiences of *practical, operational aspects* of leachate recirculation.
- Chapter 7 discusses the main potential *environmental concerns* with reference to UK operators' experience.
- Chapter 8 sets out the aspects of leachate recirculation that may require monitoring, and offers some structured suggestions on which *site-specific monitoring* proposals might be based.
- Chapter 9 presents a *summary* and the *conclusions* from the study.

2 Background

Leachate recirculation has been a feature of landfill operations for many decades. Pohland (1975) was one of the first to suggest its beneficial use as a means to enhance biodegradation, settlement, gas production and leachate treatment. Within the UK, a large-scale experimental study of these aspects was initiated by WRc at Seamer Carr in the late 1970s (Barber and Maris 1984, Blakey and Maris 1987). A further large-scale test cell study of leachate recirculation at high rates, with similar objectives, known as 'Landfill 2000', was undertaken from 1991 to 1995 (Blakey *et al*. 1997). Following the implementation of the Control of Pollution Act, 1974, and the more widespread recognition of the polluting potential of leachates to waters, the main reason for leachate recirculation from the late 1970s onwards was to provide a form of leachate control and management. At this time there was considerable research into the absorptive capacity of refuse (e.g. Holmes 1980) and the benefits of large surface irrigation systems to encourage evapotranspiration (e.g. Robinson *et al*, 1982). Papers from a Landfill Leachate Symposium held at Harwell in 1982 discuss both these aspects, and Palmer (1982) says in a section on leachate disposal that 'it is probable that most spray irrigation systems have been introduced as expedient measures to dispose of leachate' and goes on to discuss both recirculation through the landfill and spraying on to land. Over the last 10 years it has become more widely recognised that leachate recirculation can also benefit various other operational and landfill process control objectives.

The Environment Agency Sector Guidance Note for Landfill (SGN 5.02, March 2009) includes some guidance on leachate recirculation.

There may be a current perception within the UK that leachate recirculation is not compatible with the controls on leachate heads that arise from the landfilling philosophy of containment and leachate prevention, dominant from the 1980s onwards in the UK. Practical evidence relating to this aspect is considered in the review. However, as the aim of sustainable landfilling practice is to bring wastes to a sufficiently stable, non-polluting state before the engineered features become ineffective, accelerated biodegradation and flushing are likely to become essential. This will inevitably involve water addition and/or leachate recirculation at high rates. It is therefore appropriate to develop techniques and control procedures that achieve the objectives of recirculation, while also ensuring continued control over pollution risks. There is a recognition of this in many countries outside the UK, where researchers are actively investigating the concept of bioreactor landfills, an operational practice that relies heavily on the distribution and movement of moisture throughout the landfill mass.

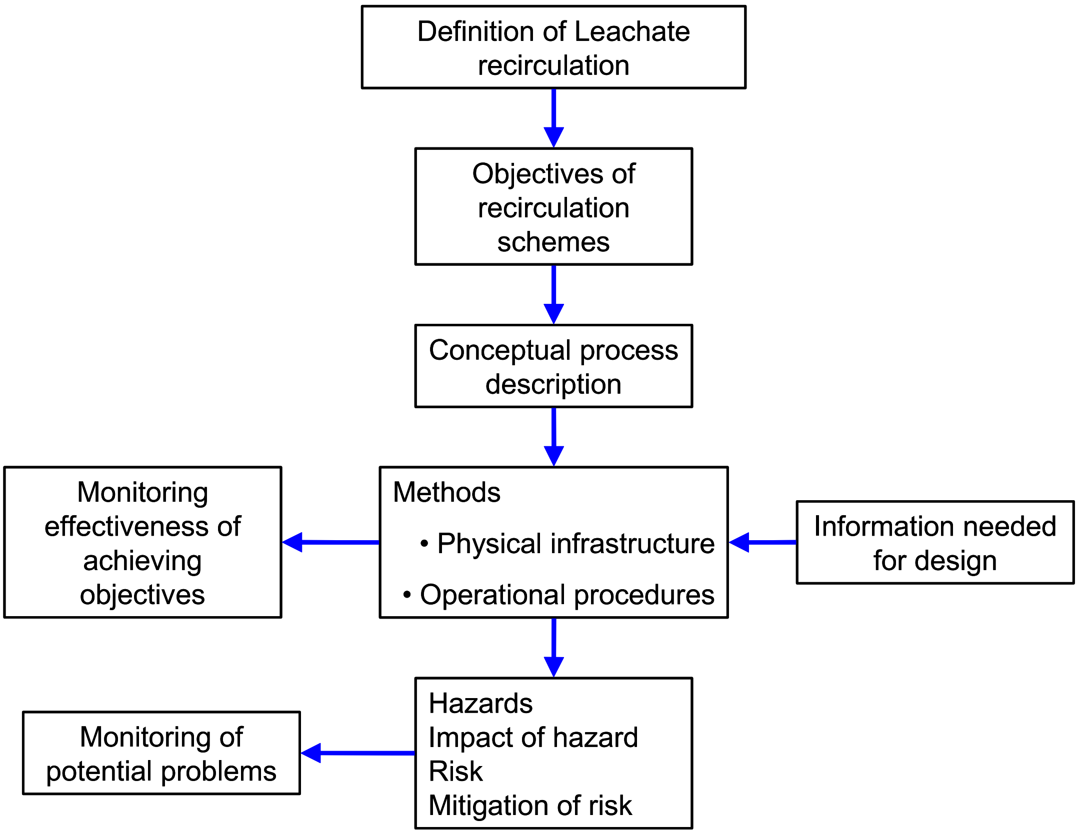
In the USA, where subtitle D landfill regulations are highly prescriptive and stringent, leachate recirculation is permitted. A major research programme into bioreactor technology, sanctioned by the EPA, has been in progress for at least a decade (e.g. USEPA 1995, ITRC 2006). Other large field-scale programmes are being undertaken in France, the Netherlands, Canada and Australia (see Section 4). The dominant drivers behind many of these bioreactor projects are increased financial returns from energy derived from landfill gas, and more rapid organic stabilisation.

On the basis of the authors' experience and a review of the relevant literature, a framework was developed that identifies the key technical, environmental and operational (including monitoring) issues that should be considered in any scheme involving leachate recirculation (Figure 2.1). The framework covers all aspects relating to leachate recirculation, including objectives, design considerations, implementation and monitoring.

The framework was used in two main ways:

- as a template in this study for identifying important topics and to form the basis of discussions with operators;
- following further development, as the basis of a checklist that regulators can use when assessing proposals from operators to undertake leachate recirculation.

Figure 2.1 Conceptual framework for considering leachate recirculation.

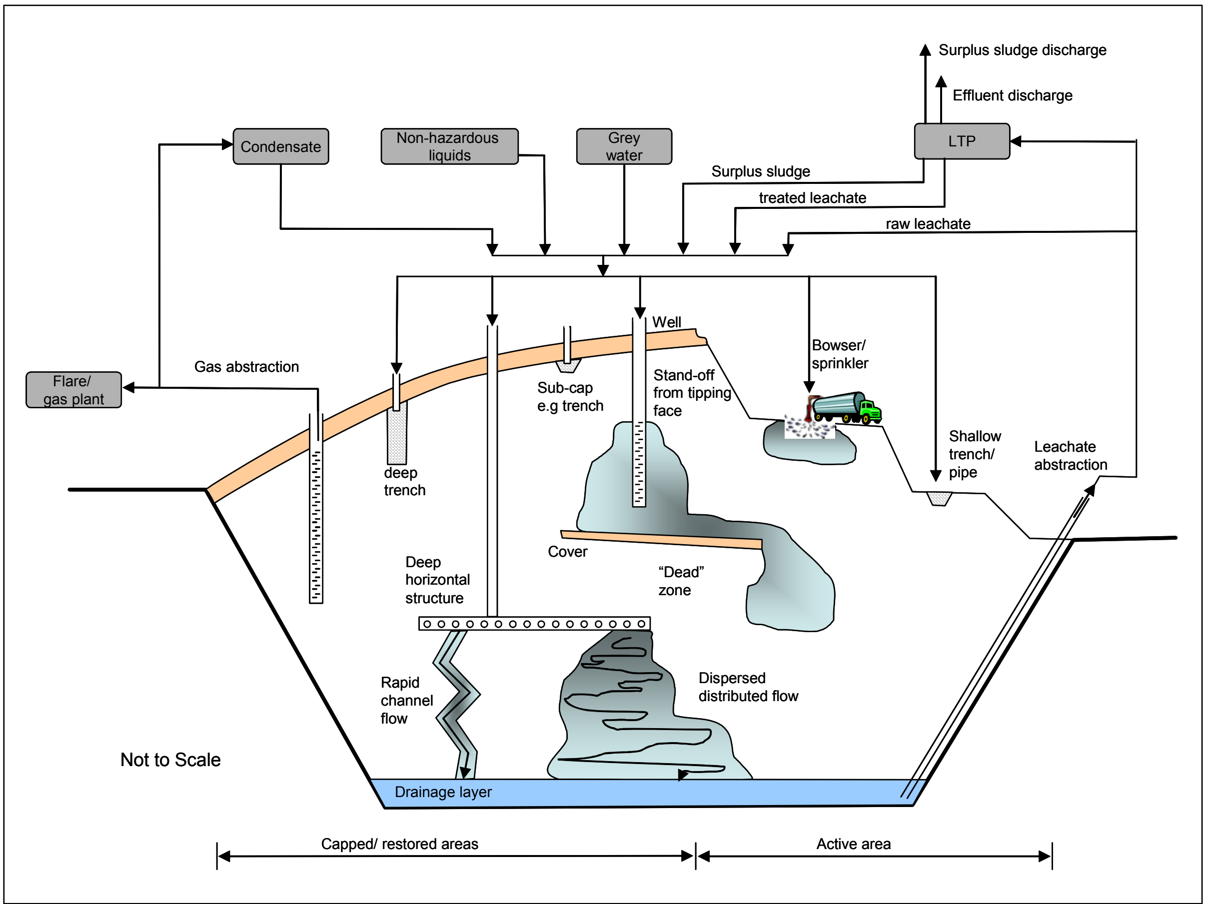


2.1 Definition of leachate recirculation

Leachate recirculation is defined in Environment Agency guidance LFTGN03 as: 'the practice of returning leachate to the landfill from which it has been abstracted' (Environment Agency 2004). Within the context of this review, we have expanded the definition to include the introduction of any liquids into a landfill. This allows us to consider experiences from the introduction of liquid wastes (a practice now banned in the EU by the Landfill Directive) and surface water collected on site. In the USA, where an extensive bioreactor Research Development and Demonstration programme has been sanctioned by the EPA (USEPA 2004, Benson *et al*. 2007) many sites are reliant on the introduction of non-hazardous liquid waste (e.g. gulley washings) to provide moisture to recirculate within the landfill bioreactor. We have not considered those systems where the aim is to evaporate the water from leachate drawn to the surface (e.g. irrigation of short rotation coppice or spraying on the cap).

A schematic showing the main elements that may be present in a leachate recirculation system is shown in Figure 2.2.

Figure 2.2 Schematic showing the main elements of leachate recirculation systems.



2.2 Objectives of recirculation schemes

The possible reasons for undertaking leachate recirculation are more numerous than might at first be appreciated. They include:

- Seeding new basal drainage layers to establish methanogenesis

  (to protect basal drainage layer from clogging from acetogenic leachate and to minimise COD in leachate collected from new phase)

- Managing leachate quality feed to leachate treatment plants

  (to prevent COD peaks reaching a Leachate Treatment Plant (LTP) designed for methanogenic leachate)

- Managing leachate flow rates (peak flow buffering/absorptive capacity)

  (to buffer peak flows and provide a more even flow to leachate treatment and disposal facilities)

- Accelerating settlement/increasing airspace

(to accelerate physical stability of waste prior to final restoration, and accelerate progress towards Completion)

- Stimulating gas generation

  (to increase landfill gas (LFG) revenues)

- Accelerating stabilisation of organic waste

  (to accelerate progress towards landfill Completion [also known in other Countries as 'Final Storage Quality'] and reduce long-term aftercare costs and liabilities)

- Flushing of contaminants

  (to accelerate progress towards Completion and reduce long-term aftercare costs and liabilities)

- Controlling fires/reduce elevated temperatures

  (to use leachate to reduce temperature of 'hot spots' in wastes or to put out subsurface landfill fires)

- Raise temperature by injecting heated leachate to stimulate methanogens in cold winter conditions

There are examples of schemes that have been implemented to address all of the above objectives, except contaminant flushing. However, contaminant flushing is being actively considered as part of a remediation scheme that the Environment Agency is commissioning for an orphaned landfill at Helpston, UK. We are currently only aware of schemes to seed basal layers to establish methanogenesis in landfills outside the UK. Practical details of these schemes are not yet in the public domain.

2.3 Conceptual process description

In most engineering projects, a conceptual process description is developed at an early stage to provide the template for detailed design, construction, operational and control purposes and for deriving cost estimates. This disciplined approach has not generally been applied to leachate recirculation schemes. The scale and design details of a leachate recirculation scheme will depend on the objectives of the scheme. Quantities of leachate requiring recirculation for three different objectives are considered below: these vary from as little as 5 litres leachate/tonne of waste to possibly 3000 litre/tonne. The scale and robustness of any leachate recirculation infrastructure will be very different depending on the volumes of leachate requiring injection, and consequently it is important to be clear about the objectives and process concept before implementing any scheme.

2.3.1 Seasonal flow balancing for leachate [typically 5–20 litre/tonne]

Seasonal flow balancing is one of the most common reasons for recirculation. It uses the storage capacity in landfills to balance peak flows in leachate production that will normally occur in winter. The benefits are that it can help prevent over-design of leachate treatment plants, reduce the requirement for short-term tankering, or the need for large leachate holding tanks or lagoons.

The scale of leachate recirculation needed for flow balancing is site specific and will be related to factors such as geographic location and seasonal rainfall, cell geometry and waste inputs. However, an estimate of the scale of leachate recirculation needed for flow balancing under typical UK conditions is shown in Table 2.1. In modern landfills, the potential volumes requiring recirculation may often be less than the values in Table 2.1, because some of the winter surplus can be allowed to accumulate within the basal drainage system of the landfill. Landfills with a flat horizontal basal drainage system would have a greater capacity to store leachate in this way than liners built on a gradient. Although these volumes of leachate recirculation are relatively modest, the infrastructure may need to be capable of delivering the required rates over a relatively short period of time, of a few weeks or months.

Table 2.1 Estimate of scale of recirculation needed for seasonal flow balancing at UK landfills.

	Value	Units
Winter surplus rainfall, in excess of discharge capacity, say	100–200	mm
Average waste depth, say	10–20	m
Average waste density, say	1	t/m^3
∴ low end recirculation rate needed [100 mm/20 t]	5	litre/t
∴ high end recirculation rate needed [200 mm/10 t]	20	litre/t
∴ annual volume for 1 M tonne of *in situ* waste	5000–20,000	m^3/year

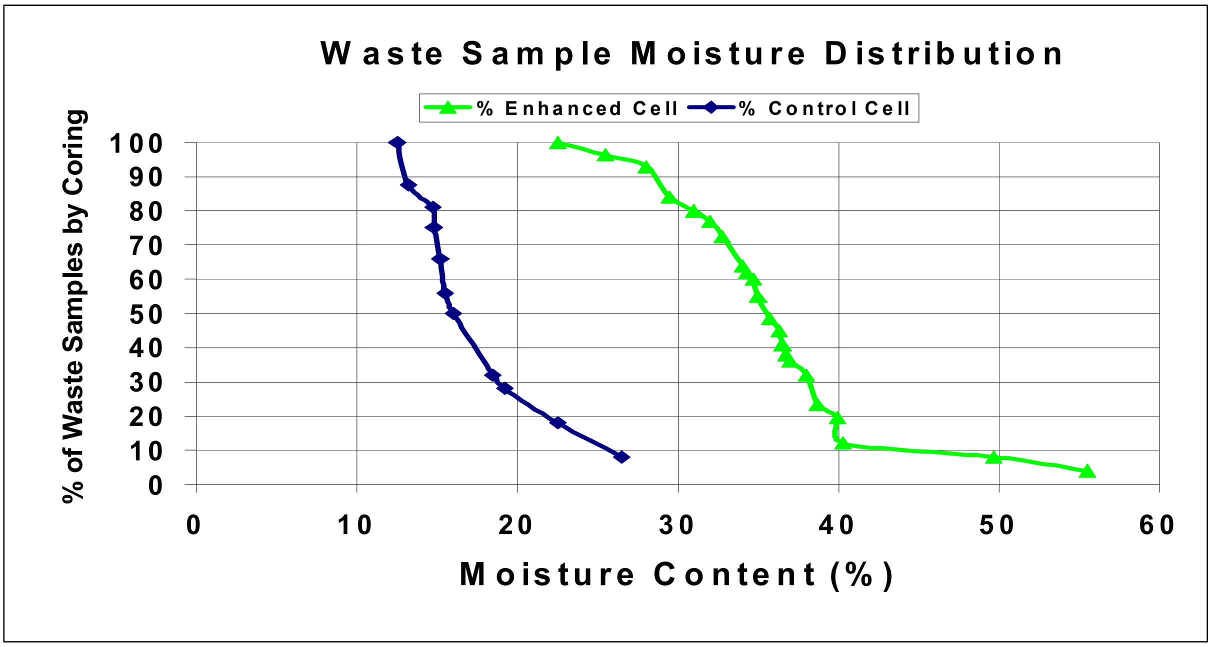
2.3.2 Stimulate gas generation [100–200 litre/tonne]

Numerous researchers during the last 30 years have shown a direct correlation between moisture content and gas generation rates (e.g. Rees and Grainger 1982, Kasali and Senior 1989, Burton *et al*. 2004). Moisture movement has also been shown to be important (e.g. Klink and Ham 1982). Improvement of gas generation and acceleration of stabilisation are very common reasons given by operators for carrying out recirculation.

To make a significant difference to the rate of gas generation within a landfill, it would be necessary to raise the moisture content of a significant proportion of the wastes by a percentage large enough to stimulate a significantly higher specific rate of gas generation in the affected parts. For example, a process concept might be to raise the moisture content of 90% of the wastes by an average of 10%. The Yolo County experiment in the USA (Mehta *et al.* 2002, Augenstein *et al*. 2005a, 2005b) took this approach on a ~10,000 tonne test cell. Recirculation and water addition increased the moisture content of waste cores by ~200 litre/tonne, from a median of ~15% to a median of ~35% (Figure 2.3). This led to more than a doubling of methane yield compared with the control cell, consistent with the literature cited above. Further details of the Yolo County field trials are given in Section 4.

Unlike leachate recirculation required for seasonal flow balancing, the time over which the increase in moisture content for gas enhancement is achieved (and hence the recirculation rate) is a matter of design. Raising of moisture content at Yolo County was carried out mostly over the first ~2 years. At many full-scale landfills, the quantities involved in raising moisture content by 10 to 20% would dictate a much longer timescale. For a 1 megatonne (Mt) landfill, the quantity of water needed would be 100,000 to 200,000 m^3. To apply this in 2 years would involve water or leachate injection rates of 50,000 to 100,000 m^3/year.

Figure 2.3 Increase in water content of waste cores as a result of recirculation (reproduced with permission from Augenstein et al. 2005a).



2.3.3 Contaminant flushing [3000 litre/tonne]

The process concept for contaminant flushing might be to achieve a desired increment in Liquid/Solid ratio each year, or to flush a defined quantity of a key contaminant (e.g. NH_4-N) from the waste each year. The volumes required for contaminant flushing are an order of magnitude higher than for other objectives. To reach Completion,[1] a volume of typically ~3000 litre/tonne might be needed, based on achieving the passage of about seven bed volumes of leachate through the wastes at a moisture content of approximately 40% (Knox 1990).

The examples given in Sections 2.3.1 to 2.3.3 are included to illustrate the benefit and need for a conceptual design. It is recommended that this be done for every application of leachate recirculation. Some will require low volumes applied in a localised manner. Others will require much larger volumes, applied over a high proportion of the landfill area. It is also recommended that these details be included in leachate management plans.

2.4 Summary of UK operations in leachate recirculation

A central part of the current project was a high level review of practice by UK landfill operators. The intention was to provide an overview of current and past activity relating

[1] For a landfill to reach a state of Completion, it must no longer pose any future threat of pollution to the surrounding environment. To achieve this state at many landfills inorganic pollutants and hard COD will need to be removed from the landfill by a process of flushing.

to leachate recirculation, without examining individual sites in detail. Six of the major UK waste management companies were contacted and asked a series of questions to provide an overview of activities at approximately 90 landfills. The following information was requested:

- number of sites/schemes in which leachate recirculation had been operated or attempted;
- objectives of recirculation;
- duration;
- scale of operations;
- nature and extent of monitoring;
- problems or success stories;
- whether part of a managed R&D programme;
- any externally funded studies (e.g. landfill tax);
- publications or policy on releasing data;
- experience with regulators.

The main reasons why the UK operators are undertaking, or are interested in, leachate recirculation are summarised in Table 2.2. There is currently a great deal of interest in leachate recirculation, driven partly by day-to-day practical requirements of leachate management (e.g. balancing flows), but also by the desire to optimise gas generation and utilisation rates from sites. There were many examples where the installed capacity of landfill gas engines exceeded the present output of gas from the site, so there was a strong commercial desire to increase gas flows and generate more power. Primary responsibility for the development and implementation of leachate recirculation schemes had been handed over to the gas utilisation team by one operator. One operator was engaged in a £500,000 R&D programme into leachate recirculation. At least two other operators have spent a considerable amount of time, money and effort on designing, developing and monitoring leachate injection infrastructure.

Table 2.2 Summary of attitudes and objectives of six major UK landfill operators.

Operator	No. of schemes	Comments
A	18	Been recirculating since 1997. Would like to do it at all their sites. Provision for recirculation was written into all their PPC permits. Main uses currently: flow balancing (designs are based on water balance calculations) stimulate gas generation temperature control (cooling)
B	>20	Generally high level of interest and positive view of recirculation. Detailed study of one scheme undertaken as far back as 1996. Intention is to carry out more instrumented, monitored schemes in the next few years. Main uses: stimulate gas generation leachate flow balancing/utilise absorptive capacity temperature control (cooling)
C	1	Would like to do it at all their sites. Main objective: accelerate stabilisation of the sites
D	~22	'We should be doing it at all our sites, to promote faster rates of stabilisation.' Main uses: flow balancing leachate quality management stimulate gas generation
E	3	Regard it as essential. Detailed in-house evaluation of a trial was undertaken in 1991 and concluded: 'Recirculate, recirculate, recirculate'. Main uses: flow balancing leachate quality management dust suppression
F	23	Generally very positive attitude. Main uses: flow balancing/head control stimulate gas generation dust suppression

3 Summary of recirculation infrastructure used by UK operators

The survey of UK operators indicated that a wide variety of different leachate recirculation systems have been used, on varying scales and with varying degrees of success. In most cases there was little technical basis for the design of the schemes. We have classified the systems into seven broad classes as follows, with some examples of quantities. The quantities are as reported to us by operators, or in some cases derived from internal reports or literature.

3.1 Low pressure surface application

At its simplest level this category includes the use of a bowser/sprinkler bar to irrigate leachate at the tip face. Other systems include open trenches or pits dug in the surface of the waste, and open-ended pipes laid on the waste surface. Pits achieve very localised ‘point-injection’, whereas application at the tipping face achieves, by definition, a broad distribution.

Examples:

Bowsers at working face: 10–40 m^3/day; 10,000 m^3/year; 10,000 m^3/year; 12,300 m^3/year; 13,000 m^3/year.

Open pipe, pumped direct from sump: 50–100 m^3/day.

Bowser used for dust suppression: 2800 m^3/year.

Figure 3.1 Example of low pressure surface application via drainage stone and open pit.

3.2 Systems immediately below top liner

These types of system tended to be linear (i.e. tyre or rubble filled trenches) or perforated pipes in a trench filled with drainage material. Some systems were designed to be perfectly horizontal and some to include a fall in the trenches.

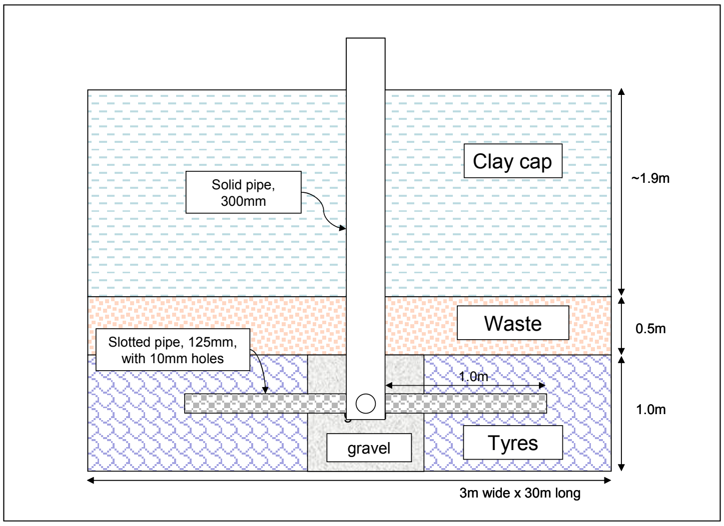
Examples:

Tyre filled trench 30 x 3 m x 1 m deep took ~25 m^3/day (~270 mm/day).

One operator, eight sites, annual quantities: 100, 162, 3600, 6561, 11,000, 11,300, 20,000–25,000, 35,000 m^3/year.

Slotted pipe (100 mm) in gravel-filled trench, 20 m long x 0.9 m wide x 1 m deep, beneath 2 m clay cap, took ~1000 m^3 in ~1 year; average rate thus ~50 m^3 per linear metre per year. Rates were limited by availability of leachate and reached ~90 m^3/m/year at times. Areal rate on base of trench was ~55 mm/year (mean) and 100 mm/year (peak).

Figure 3.2 Example of leachate reinjection trench installed below clay cap.



3.3 Horizontal linear structures at depth within wastes (i.e. constructed during infilling)

At least two operators had used 'spiders' consisting of horizontal pipes connecting radially to a central access sump/pipe that was raised as landfilling progressed. The radials come off at different levels within the landfill. Most operators had used some form of horizontal pipes or trenches within one or more of their landfills. A typical design would involve HDPE pipes with a diameter ranging from 32 to 150 mm, often installed in a stone or tyre-filled trench. Although one operator had a design that recirculation trenches should be at 50-m centres this was not achieved and very often the distance between trenches would be 100 m or more.

Example:

800 m of buried 32-mm pipe injected 2235 m^3 over 6 months (5.6 m^3 per linear metre of trench per year). At 50 m pipe spacing, areal rate on landfill cell was ~111 mm/year.

3.4 Subsurface pads of drainage material (constructed during infilling)

A variation on subsurface trenches is rectangular pads filled with drainage material, often whole or shredded tyres. The type of design varied from a 20 x 40 m grid of small 1 x 1 m pads of drainage material with individual access pipes connected to a central well, to single large pads of tyres, the largest being 50 x 50 m x 2 m deep with a vertical access pipe. In terms of performance the larger individual structures performed a lot better than the smaller multiple ones.

Example:

50 x 50 m tyre pad accepted ~9000 m^3 of leachate over a 5 month period (~60 m^3/day; ~8.6 m per year, or ~24 mm/day). Long-term performance was not assessed.

Figure 3.3 Example of subsurface tyre pad during installation (tyres covered with geofabric).

3.5 Subsurface band drains (constructed during infilling)

One operator (following limited success with other types of infrastructure) had developed and implemented a system based on band drains. These are geotextile drainage ‘socks’ installed by percussion at 1-m centres on a 40 x 40 m grid, to alternating depths of 5, 10 and 15 m. The top surface of the ‘socks’ is then overlain by a bed of drainage material to distribute injected leachate evenly over the whole area. This is accessed from the surface by a vertical pipe. The first of these systems was installed in 1998.

Example:

An injection rate of 200 m^3/day was maintained into one system over a period of 45 days (recirculation rate ~45 m/year, or ~123 mm/day).

Due to a lack of leachate to recirculate, the long-term performance of these systems has not been assessed. If it continues to work (and if the geotextile socks do not clog) this is a highly impressive and innovative method of leachate recirculation. The close spacing of individual band drains means that many of the problems associated with the heterogeneity of the waste are effectively engineered out. The combination of vertical and horizontal injection structures also overcomes problems with layering.

Figure 3.4 Example of band drain used for leachate recirculation.

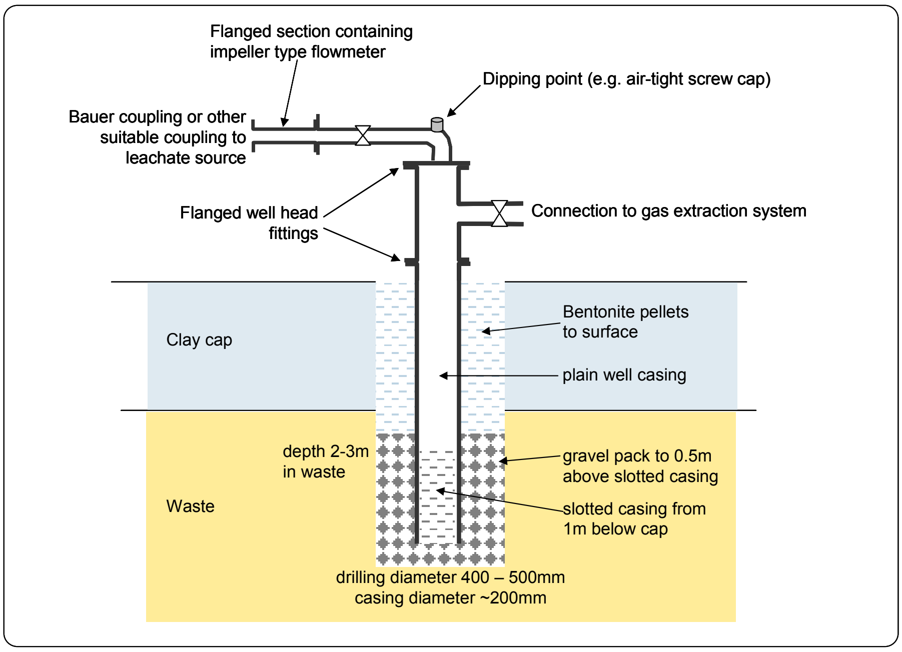
3.6 Vertical wells

Most operators have used some vertical wells for leachate injection. Usually they have utilised existing leachate abstraction/monitoring wells or gas wells. A few operators have investigated the use of pin wells. These are percussion installed wells approximately 5–10 m deep typically at 20-m centres on 80 x 100 m area. No data on performance of pin well systems was obtained.

Example:

Purpose-built linked sets of four shallow drilled wells extending ~2 m into waste below restoration layers. The four wells are linked to a common header tank, maintaining a constant ~3 m head. These sets have sustained daily rates of ~55 m^3/day over periods of more than a year. Suspicion of possible short-circuiting to nearby deep gas well.

Figure 3.5 Example of injection well design for use in leachate recirculation.



3.7 Deep vertical trenches

Deep vertical trenches have been used, both for the injection of liquid wastes and for recirculation. Trenches of ~6–8 m deep, by ~1.5 m wide, filled with tyres and covered with geofabric prior to being surcharged with waste have accepted liquids via vertical access pipes.

Examples:

Liquid wastes at 75–100 m^3/linear metre/year (~140 to ~180 mm/day).

~130,000 m^3 of leachate recirculated via ~1300 m of trench in one month. At a trench width of 1.5 m, this is equivalent to 2150 mm/day. At 50-m spacing, areal rate would be 24,000 mm/year.

Figure 3.6 Example of deep tyre-filled trench, covered with geofabric.

4 Recirculation experiences outside the UK

To help put UK practice, experience and regulatory attitudes into context, literature on a number of large-scale and reasonably well-instrumented recirculation schemes in other countries is considered below.

Reinhart (1996) reviewed case studies of eight full-scale leachate recirculation landfills in the USA and relevant information is discussed below, and summarised in Table 4.1.

4.1 Southwest landfill, Alachua County, Florida

Surface infiltration ponds were used at this site over a 2-year period (1990–1992) for the recirculation of leachate into the top of a 20-m deep site (Townsend 1995). Four ponds were used with a total basal area of 4670 m^2. Classical water balance techniques (water inputs – water outputs = change in storage), which took into account evaporation and surface water and leachate inputs to the ponds, were used to determine infiltration rates. The highest infiltration rates occurred in the few weeks directly after starting to use a pond, and then reduced to a much lower steady state rate. One of the ponds was constructed over a vertical gas vent, and much larger infiltration rates were achieved. Townsend (1995) calculated that a representative steady state infiltration rate (excluding the impact of the gas vent) ranged from 6×10^{-6} to 9.1×10^{-6} cm/s (52 to 79 m^3/ha/day) and was on average only twice the amount lost through evaporation from the pond. No problems with odours were reported during the 28 months of operation. The steady state infiltration rates were used to calculate the vertical hydraulic conductivity of the waste at the surface, which varied between 3.1 and 4.0×10^{-8} m/s. Townsend attributed these low values to a number of factors including waste compaction and landfill gas production. The presence of gas bubbles in the base of the ponds was noted. The impact of gas production on lowering the hydraulic conductivity of waste by over an order of magnitude has been demonstrated by Hudson *et al*. (2001).

A second leachate injection system based on horizontal pipes placed in individual lifts of refuse was installed in a new area of the same site in 1993 (Townsend and Miller 1998). A total of 11 laterals were constructed, with a vertical spacing of 6 m and a horizontal spacing of 15 m. Each lateral was between 110 and 238 m long, and they were generally installed in a 1-m wide trench backfilled with tyre chips to a depth of 0.3 m. Overall 1738 m of injection pipe was installed, with a trench basal area of 1738 m^2. Reinhart (1996) (reporting the work of Townsend and Miller) assessed the early performance of the laterals. A total of 7600 m^3 of leachate was pumped into two laterals over a period of 6 weeks without exceeding an injection pressure of 55 kPa at the pump. This equates to an injection rate of ~0.6 m^3/metre trench per day. Over a 19 month period 30,000 m^3 of leachate was injected into 11 laterals giving a much lower average injection rate of 0.03 m^3/metre trench per day (~11.6 mm/day). However, short-term injection was related to injection pressures and ranged from 0.29 to 0.38 m^3/metre trench per day per metre of applied water head. Water heads up to 15 m were applied to certain laterals. High pressure injection did result in some occurrences of surface seeps from injection lines located near the surface of the landfill. Townsend and Miller (1998) also reported a reduction in flow rate into the laterals and an increase in injection pressure over a timescale of several hours.

Figure 4.1 Leachate injection infrastructure at Southwest landfill, Alachua County, Florida.

Photographs source: http://www.cluin.org/wales/download/Townsend_usa_landfills.ppt

4.2 Pecan Row landfill, South Georgia

A high pressure 150 mm OD delivery main pumped leachate into 457 m of perforated pipe at different levels in waste in a 4.5 ha area. Pipes were laid in 0.9 m^2 (cross-sectional area) gravel-filled trenches. The pump was rated at 1514 l/min (90 m^3/h), and was only operated for a maximum period of 1 hour at a time. Reinhart (1996) quotes an average injection rate of 1.1 m^3/ha/day. At the time of reporting, the site had only been in operation for a maximum of 18 months and the injection rate therefore equates to a total recirculation volume of 2700 m^3 (or only 30 hours' pumping time). Again, leachate recirculation into pipes close to the waste surface or slopes led to breakout (this may be mainly as a consequence of high pressure injection, although no details of injection pressure are reported).

4.3 Coastal Regional Solid Waste Management Authority landfill, Craven County, North Carolina

Reinhart (1996) reported the use of a set of moveable shallow pin wells to increase the moisture content of the first 4.6-m-deep layer of refuse at this site. A total of 12 pin wells were installed into an area of 30 x 30 m (~10–15 m well spacing) to a depth of 3 m (increased from an initial depth of 1.5 m because of problems with rapid outbreaks of leachate at the surface). Delivery pressures of 310 kPa (45 psi) led to recirculation rates of 208–303 l/min for period of 2–8 days. Assuming 8 hours per day operation, then over 4 days injection rates of ~0.5 m^3/m^2 were achieved. This appears to be a good method of increasing the water content of waste shortly after placement, but obviously does not create a long-term leachate recirculation infrastructure.

4.4 Central Solid Waste Management Center, Delaware

Long-term monitoring studies of leachate recirculation at a landfill in Delaware was reported by Morris *et al*. (2003). Leachate recirculation over a 10-year period (1985–1995) was undertaken within two landfill areas (A/B) with a combined surface area of 10.9 ha. Leachate recirculation was carried out using a mixture of leachate injection wells, spray irrigation and a sub-cap horizontal leachate recirculation field. The vertical recharge wells were initially backfilled with pea gravel (to act as an aerobic filter) but they soon clogged with precipitates. The design was changed to a system based on 1.2-m diameter perforated concrete rings backfilled with 'large stones' (Yazdani *et al*. 2006, quoting Vasuki 1993). A total volume of 72,000 m^3 was recirculated over a 10-year period into a waste mass of 642,000 tonnes. Morris *et al*. (2003) calculate that this volume represents 0.13 m^3/tonne, or approximately 90% of that which was required to raise the water content of the whole waste mass in area A/B to field capacity. Two 0.4 ha test cells with approximately 8000 tonnes of waste were constructed in 1989 to compare the effect of leachate injection (Cell 1) with a control (Cell 2). Leachate injection was through a leach field consisting of perforated pipes in aggregate-filled channels over an area of 10 x 15 m. A total of 1920 m^3 was injected over a 6-year period into Cell 1, representing a total volume of ~0.2 m^3/tonne. However Yazdani *et al*. 2006 (quoting Vasuki 1993) reported that the water content of much of the waste in the enhanced cell remained well below field capacity and that decomposition was very varied throughout the cell.

4.5 Yolo County Bioreactor

A USEPA approved Project XL (eXcellence and Leadership) is being undertaken at Yolo County Central Landfill to investigate the concept of the bioreactor and involves a leachate recirculation trial in a 70,000-ton bioreactor. This trial follows on from a previous trial in Yolo County in two 9000-ton test cells. Other Project XL bioreactor trials include Buncombe County Bioreactor landfill, Anne Arundel Bioreactor Landfill and Virginia Landfill. Details and further links to these projects can be found at http://www.epa.gov/projectxl/implemen.htm

In 1994 two 9000-ton (8164-tonne) tests cells were constructed, one being a control and the other being an 'enhanced' cell operated with managed additions of water and recirculated leachate. A daily cover of shredded green waste was used rather than conventional soils. The cell dimensions were approximately 30 x 30 m in area with a maximum depth of 13 m, giving an airspace for waste materials of approximately 12,000 m^3. Leachate was added through a grid of 13 injection pits (each with an assumed base area of 10 m^2), at a spacing of ~8 m, located near the surface of the waste and backfilled with scrap tyres (Augenstein *et al*. 2005b). Irrigation and leachate recirculation occurred through this infrastructure from 1995 to 2003. Initial irrigation rates over the first 3 months were between 1 and 3 cm/day (averaged over the full surface area of the enhanced cell), a rate that caused no problems to the leachate recirculation infrastructure. Water balance techniques indicated that approximately 1600 m^3 of moisture was absorbed by the waste in the first 3 months, indicating an average water uptake of 19%. Data from discrete *in situ* moisture sensors in the waste also indicated that the recirculation had caused a reasonably homogeneous distribution of moisture throughout the cell. Recirculation of leachate in the longer term was at a rate of 100 cm/year (~0.3 cm/day). Over 9 years of operation 8000 m^3 of leachate has been recirculated into the control cell, with very little in the way of operational problems. The researchers responsible for the trial are very clear in their belief that the use of 'permeable' green waste daily cover was a key factor that contributed to their ability to distribute the volumes of water evenly through out the cell. Clear evidence of enhanced methane production and settlement is presented for the enhanced cell compared to the control cell.

The Project XL trial at Yolo County Central Landfill involved the construction of two anaerobic bioreactor cells and one aerobic cell, all with a combination of liquid addition and leachate recirculation (Yazdani *et al*. 2006; http://www.yolocounty.org/recycle/bioreactor.htm). The two anaerobic cells (designated NE 3.5-acre cell and W 6-acre cell) had a surface area of 1.4 and 2.4 ha respectively, and were filled to a depth of approximately 15 m with four lifts of waste. Although the use of green waste as a daily cover was maintained, soil cover also had to be used as cover in certain instances. The leachate injection infrastructure was based on 32 mm OD HDPE pipe installed between waste lifts at spacings that varied between 12 m for lower lifts and 8 m at the surface. The injection lines were installed on a levelled area graded with green waste. The lines were ‘snaked’ to allow for future settlement. The HDPE pipe was perforated with 2.3-mm holes, a single hole being drilled every 6 m along the pipe. The rationale behind this slightly surprising design decision was to create conditions that would allow even distribution of flow along the pipe. It can be calculated (based on flow rates summarised in Table 4.1) that the average velocity through each hole was 0.23 m/s, a perfectly reasonable parameter (assuming there has been no reduction in surface area through clogging). Each injection hole was covered with pea gravel to help prevent clogging, and the whole line was covered with shredded tires to protect it from waste placement. Yazdani (pers. comm., 10 January 2006) reported that there were some initial problems with clogging from high pH (pH 8.5–9) liquids, but in normal operation there have been none. A total of 2500 m of piping was installed in the NE 3.5 acre cell with a total of 342 injection holes (open area 1.4×10^{-3} m^2), and 2200 m of piping with a total of 321 injection holes (open area 1.3×10^{-3} m^2) was installed in the west 6-acre cell.

Liquid addition and leachate recirculation in the NE cell started in February 2002 and over a 3-year period 20,800 m^3 was introduced. This equates to an infiltration rate of 13 m^3/ha/day.

Liquid addition and leachate recirculation in the larger west cell started in May 2003 and over a 22-month period (until March 2005) 17,400 m^3 was introduced. This equates to an infiltration rate of 11 m^3/ha/day. During the first phase of liquid injection, the infrastructure was tested to find out what the upper rate of injection would be. An injection rate of 160 m^3/ha/day was maintained for a period of 14 days but led to leachate seeps occurring at the western side slopes of the cell. This appeared to open up flow paths that may not have been created under a less aggressive recirculation regime, because leachate seepages remained even when much lower recirculation rates were tried subsequently. A cut-off trench had to be installed along the full width of the western slope to control the seeps.

Throughout the period of operation of the leachate recirculation system, the leachate head on the liner has been maintained at less than 5 cm in both cells.

4.6 New River Regional Landfill Bioreactor Project, Florida

The bioreactor demonstration project being undertaken at the New River Regional Landfill (NRRL) is another major research project in the USA involving leachate recirculation. The overall site comprises six cells and is approximately 18 ha, of which two cells and 4 ha are operated as an active bioreactor. The maximum waste depth is approximately 22 m. Further details of the site can be found at http://bioreactor.org/nrrl/. A total of 134 vertical wells in 45 clusters (comprising three closely spaced wells each screening different horizons) were installed in the test area (Jain *et al*. 2006). The well clusters were spaced 15 m apart. In total approximately 670 m of 50-mm-diameter screened well was installed. Between 1 June 2003 and November 2004, approximately 17,800 m^3 of leachate and groundwater was injected into the well field, averaging 34 m^3/day, or 0.25 m^3/day per well (although not every well was used). Between January and November 2004 the injection rate was nearer to 50 m^3/day. However, the majority (14,600 m^3) of the liquid injected into the boreholes was undertaken as part of studies (Jain *et al*. 2006) to assess the permeability of the waste, and was injected into only 77 wells. The research involved the continuous injection of leachate into wells (up to 12 at a time) over periods of several days or weeks until steady state conditions were achieved. The rate of injection was related to injection pressure. Within the deeper wells higher injection pressures were applied (by allowing the well to fill to near the surface) than in the shallow wells. Consequently, even though interpretation of the data suggested that waste hydraulic conductivity reduced with depth, higher steady state injection rates were achieved in the deep screened horizons (typically 700 l/m/day) than in the shallow horizons (144 l/m/day, data interpreted from Jain *et al*. 2006). In all tests injection rates reduced with time.

4.7 Waste Management Inc Bioreactor programme

Waste Management Inc has been operating at least ten full-scale bioreactor demonstration projects in the USA and Canada. Further details and links to the projects can be found at http://www.wm.com/WM/environmental/Bioreactor/index.asp. Perhaps the most comprehensive research is being undertaken in conjunction with the USEPA at the Outer Loop Landfill, Louisville, Kentucky. The research at Outer Loop, and on several other large-scale bioreactor landfills, is subject to a Cooperative Research and Development Agreement (CRADA) with EPA's National Risk Management Research Laboratory. The purpose of this joint research venture, which ran between 2001 and 2006, was to assess the best operating practices to promote safe operation of bioreactor landfills.

Literature on Outer Loop has been reviewed, but detailed information on leachate recirculation application rates and volumes are not in the interim reports published to date. Further details, including a water balance, are to be included in the project's final report.

4.8 Benson *et al*. bioreactor/recirculation landfills review

Benson *et al*. (2007) undertook a practice review of five bioreactor/recirculation landfills in the USA as part of the USEPA-funded research into bioreactor technology. The review of sites was anonymous, but excluded the Yolo County and Florida-based bioreactor research. The main conclusion from the research was that the volumes of leachate that had been recirculated at the various sites were not enough to bring the waste in any of the sites to field capacity, and that longer-term studies were required. Recirculation rates averaged between 1 and 5 m^3/ha/day, similar to the rates at many of the other research sites summarised in Table 4.1. There was little difference in leachate heads, generation rates, temperature and liner temperature between the bioreactor landfills and conventional sites, although there was some evidence that leachate with a higher organic strength was produced in the first 2–3 years of operation.

4.9 Leachate recirculation studies in France

Both SITA and Veolia have been undertaking bioreactor research in Europe.

SITA initiated leachate recirculation research at their 2.25 ha Busta landfill site in northern Italy in 1999. The site has an airspace of ~385,000 m^3. A leachate recirculation system involving five 130-m long horizontal injection trenches at 25 m spacing was installed 3 m below the surface, approximately 21 m above the base (Barina *et al*. 2001). Subsequent landfilling has placed a further 3–14 m of waste (depending on location) above the trenches, and a second horizontal system has been installed below final cap level. The 75-mm-diameter PVC perforated pipe was installed at the bottom of a gravel-filled trench that had the dual purpose of leachate injection and gas extraction. A 110-mm perforated HDPE pipe was installed in the top part of the trench for gas extraction, with the two pipes being separated by an HDPE membrane. Approximately 200 m^3 per month was recirculated into the system over a 14-month period between August 1999 and October 2000, and thereafter Barina (2005) reported that 0.013 m^3/t/year has been recirculated regularly, equivalent to ~5000 m^3/year.

The early research at Busta led on to more detailed investigations at the Drambon site, near Dijon, France, in collaboration with Cemagref (a national French research institute). The aim of the ongoing research is to evaluate the performance of a carefully designed horizontal leachate recirculation network and its impact on settlement, waste degradation and leachate quality (Barina *et al*. 2003). A main emphasis of a preliminary study at the site was to investigate the zone of influence of horizontal trenches installed at different spacings (between 10 and 25 m) and operated at different injection rates. Five 70-m-long injection trenches at spacings of 10, 15, 20 and 25 m were installed in an 8-m deep site. Two-dimensional electrical resistivity remote sensing techniques were used to assess the distribution of moisture during injection events (Moreau *et al*. 2003, 2004). Results reported so far relate to relatively short-duration (a few hours) injection events at rates between 5 and 20 m^3/hour, but Barina *et al*. (2005) report that the mean zone of influence is between 15 and 20 m, with relatively rapid drain down back to initial water content conditions over a period of 48 hours. The influence of leachate recirculation on the storage characteristics of landfill gas was noted. Over a period of 3 years following installation, localised settlement had influenced the fall on the pipes, and there had been a 23–33% reduction in the short-term flow rate accepted by the individual recirculation pipes.

A second pilot study at the site involves two 0.2 ha cells, one recirculation cell and a control cell. The average waste depth in the cells is approximately 10 m, and the test cell contains 18,000 tonnes of waste. Four horizontal combined gas extraction and leachate injection trenches were installed at a spacing of 12.5 m. Between August and October 2004, 250 m^3 of leachate was introduced into the control cell, representing an increase in waste content of approximately 1.5% of total mass. Within 2 months the cumulative gas production curves of the test and control cells, which hitherto had been identical, started to diverge. At the start of leachate injection, cumulative gas production was 5 Nm^3 CH_4/tonne in each cell. After 200 days, cumulative gas production had reached 35 Nm^3 CH_4/tonne in the test cell compared to 27 in the control (Barina 2005).

Veolia, through the endeavours of CREED, their Environment, Energy and Waste Research Centre, are running four bioreactor research projects in the USA, Australia and France (Moreau-Le-Golvan *et al*. 2005). The bioreactor site in France is at the La Vergne landfill. The test cell at La Vergne is 1.5 ha, with a waste depth between 6 and 12 m giving a total airspace of 160,000 m^3 (Bureau *et al*. 2005). It is split into three sub-cells, with approximate dimensions of 50 x 100 m. The overall injection system (covering the three sub-cells) is based on 18 small diameter (90 mm) vertical wells, either in pairs with discrete screened horizons for waste depths in excess of 10 m or with a single pipe. Overall, there are 26 discrete response zones, and it is assumed (information not provided) that there is approximately 144 m of screened well. Well spacing is at approximately 30 m. Although cumulative volumes of leachate recirculated have not been reported to date, typically 400 m^3 of leachate are injected in a month. A typical 6-week injection cycle involves only 13 days where leachate is injected. On each injection day two different wells are selected and up to 25 m^3 of leachate injected. Following a year of leachate injection, solid waste cores were obtained by drilling to determine the gravimetric moisture content with depth at varying distances from an injection well (Skhiri *et al*. 2006). Cores at a distance of 5 m from an injection well showed marked increases in water content (from an initial value of 27% to between 33 and 39% measured as per cent water by wet mass) at depths between 4 and 8 m, whereas at a distance of 15 m there was very little change from the initial value. It was concluded that the radius of influence of an injection well injecting into unsaturated waste is between 5 and 10 m.

The test cells have also been instrumented with electrical resistivity geophysics as a means to track changes in moisture content in the waste. The geophysical results at this site and two others are described by Guerin *et al*. (2004). Injection into the response zone of a vertical well (site not specified) at a depth of 4–6 m below the surface was undertaken over a 24-hour period, during which time the injection rate was gradually increased. Although flow rates are not specified, the final injection was undertaken at a pressure of 1 bar. The authors report a zone of influence of the injection borehole to be estimated at 3.6 m for a depth range of 3.5 to 5 m. The resistivity plots also depict a spreading of the zone of influence with depth. Furthermore, the results are consistent with those of McCreanor and Reinhart (1996) and McCreanor (1998) in showing that increased flow rates cause larger zones of influence. However, the attempt to inject leachate at a pressure of 1 bar had surprising results. It is believed that the high pressure caused preferential flow paths to become established (that resulted in a rapid drop in injection pressure), and the geophysics saw a stop in the continual evolution of a spreading waste wetting process.

4.10 Leachate recirculation in the Netherlands

The Dutch Sustainable Landfill Research programme is researching ways to bring landfills to an equilibrium with the environment within a period of 30 years (http://www.sustainablelandfilling.com/). The Landgraaf bioreactor test cell is investigating the flushing of soluble inorganic and stable organic compounds from the site (Woelders *et al.* 2005). The pilot test cell was constructed in 2001, has a surface area of approximately 4400 m^2, is 5–9.5 m deep (average depth 6 m) and contained 25,000 tonnes of waste at a density of approximately 1.08 t/m^3. Two leachate injection systems were installed based on horizontal pipes. One system was located approximately 4 m above the base and involved five parallel 35-m pipes at a spacing of approximately 13 m. The second system was installed just below the cap and comprised six parallel lines orientated at 90 degrees to the first set of pipes at a spacing of approximately 10 m.

Between April 2002 and April 2006, 5800 m^3 of fresh water was injected into the recirculation systems without any reported problems. This represents a water addition equivalent to 230 l/ t, one of the highest rates achieved in any field-scale experiment. In addition, during the periods when fresh water was being added, leachate was also recirculated. The authors reported the combined equivalent recirculation rate to be more than 3000 mm/year.

4.11 Summary

The information contained in the studies detailed above indicates that leachate recirculation is an operational procedure that has been widely used, and there is considerable experience of different systems and technologies. The performance of leachate injection infrastructure and operational and environmental concerns are considered in the light of both the UK operators' survey and the international context in Sections 6 and 7.

Table 4.1 Summary of overseas leachate recirculation research at the field scale.

Site	Recirculation method	Dates and duration of recirculation	Cell area covered by injection infrastructure (ha)	Length (L) and area (A) of injection infrastructure	Total volume recirculated (m^3)	Areal recirculation rate (m^3/ha/day)	Infrastructure injection rate (see footnote) T: litre/m/d W: litre/m/d P: litre/m^2/d S: litre/m^2/d	Source
Alachua County, Florida, USA	4 infiltration ponds, totalling 4670 m^2 basal area. 5.2 to 7.9 l/m^2/day	1990–1992 (473 days)	~11	A: 4670 m^2	13,117	2.5	S: 5.1–7.8	Reinhart 1996, Townsend *et al*. 1995
	11 tyre-chip-filled trenches with drainage pipes. 15 m lateral spacings, 6 m vertical spacing. 1738 linear metres	1993–1994 (580 days)	~11	L: 1738 m A: ~1738 m^2	30,000	4.7	T: 600 (short term) T: 29 (long term)	Reinhart 1996, Townsend *et al*. 1995
Pecan Row Landfill, South Georgia, USA	Perforated pipes at 30 m spacing off three pressurised force mains	Late 1992 – early 1994 (~18 months)	4.5	L: 457 m A: 411 m^2	2700 (estimated)	1.1	T: 10	Reinhart 1996
CRSWMA, North Carolina, USA	A moveable system of 12 shallow pin wells at a spacing of 10–15 m		~8.9 ha	L: 24 m (assume 2 m screen per pin) A: 900 m^2 (moveable)	No information	11.7	W: ~4000–6000 (assumed short term) S: 110–160	Reinhart 1996
CSWMC, Delaware, USA	Injection wells, spray irrigation and sub-cap horizontal seep field in Area A/B – 642,000 tonnes; 1.29 Mm^3	1985–1995 10 years	10.9	Information insufficient	72,000 130 litre/t waste	1.8	N/A	Morris *et al*. 2003
	8000- tonne test cell with horizontal pipes and control cell	1990–1996	0.4	10 x 15 m	1920 200 litre/t waste	2.2	S: 6	Morris *et al*. 2003
Yolo County test cells, USA	13 tyre-filled pits at 8 m spacings	1994–2003 (9 years)	0.09	A: 130 m^2 (assumed)	8000 980 litre/t waste	~27	P: 19 (assumed)	Augenstein *et al*. 2005b
Yolo County Project XL Bioreactor	23-mm HDPE horizontal pipes with 2.3 mm hole every 6 m	2002–2005 (ongoing) 2003–2005 (ongoing)	1.4 2.4	L: 2500 m A: 2500 m^2 L: 2200 m A: ~2200 m^2	20,800 17,400	13 11	T: 70 T: 12	Yazdani *et al*. 2006
NRRL, Florida, USA	134 vertical wells in 45 clusters at 15 m spacing	2003–2004 (ongoing)	4	L: 670 m	17,800 (to November 2004)	8.4	W: 50 (long term) W: 144–700 (steady state)	http://bioreactor.org/nrrl Jain *et al*. 2006
Landfill 'S', USA	Horizontal 100 mm OD HDPE perforated pipe in 0.6 x 0.6 m trenches backfilled with 22–38 mm washed aggregate. 60 m horizontal spacing, 10 m vertical		3.6		16 (litre/t waste)	2.3		Benson *et al*. 2007

Site	Recirculation method	Dates and duration of recirculation	Cell area covered by injection infrastructure (ha)	Length (L) and area (A) of injection infrastructure	Total volume recirculated (m^3)	Areal recirculation rate (m^3/ha/day)	Infrastructure injection rate (see footnote) T: litre/m/d W: litre/m/d P: litre/m^2/d S: litre/m^2/d	Source
Landfill 'D', USA	Horizontal 150 mm OD perforated pipe in 0.6 x 0.9 m trenches backfilled with 38–64 mm aggregate. 18 to 60 m horizontal spacing, 6 m vertical.		9.7		16.9 (litre/t waste)	0.6		Benson *et al*. 2007
Landfill 'Q', USA	Horizontal 75 mm OD HDPE perforated pipe in 1 x 1 m trenches backfilled with 12–18 mm aggregate. 20 m horizontal spacing, 6 m vertical. Gravity-fed leachate distribution system. Continuous, but sequential dosing of individual lines		12.1		419 (litre/t waste)	4.5		Benson *et al*. 2007
Landfill 'C', USA	Horizontal 100 and 125 mm OD HDPE perforated pipe in 0.6 x 0.6 m trenches backfilled with 150 mm tyre shred. 15 m horizontal spacing, 6 m vertical. Sequential dosing of lines over 1–2 days at 290 l/m per event		5.6		29.2 (litre/t waste)	1.7		Benson *et al*. 2007
Landfill 'E', USA	Horizontal 150 mm OD HDPE perforated pipe in trenches covered with 38 mm aggregate and geotextile fabric. 32 m horizontal spacing, 11 m vertical		17.8		19.1 (litre/t waste)	2.8		Benson *et al*. 2007
Busta, Italy	Horizontal 75mm OD PVC pipe in gravel-filled trenches. 5 x 130 m long trenches at 25 m spacing	August 1999 – October 2000	2.25	650 linear m of trench Above length increased by undercap trench system	2800 m^3 (over 14-month period). Between 1999 and 2005, ~30,000 m^3 ≡ 80 litre/t waste	~2.4 ~6.1	T: 10	Barina *et al.* 2001, 2003, Barina,2005
Drambon, France	5 x 70 m horizontal trenches	August–October 2004	0.5 ha 0.2 ha	L: 350 m	250 m^3	~5.5	T: 8	Barina 2005
La Vergne, France	18 injection wells with 26 response zones at 30 m spacing		1.5 ha	L: 144 m (assumed)	No information	~8.9	W: 90	Bureau *et al.* 2005
Landgraaf, Netherlands	Injection trenches 5 x 35 m at mid height of cell and 6 x ~60 m at 90° orientation under cap	April 2002 – April 2006	0.44 ha	L: 535 m	5800 m^3	9	T: 7	Woelders *et al.* 2005

Footnote **T:** Trench – litre per linear metre per day (l/m/d), based on assumed length of active trenches
W: Well – litre per linear metre per day (l/m/d), based on total screened length
P: Injection pads – litre per m^2 per day (l/m^2/d), based on base area of pads
S: Surface application – litre per m^2 per day (l/m^2/d), based on surface area covered

5 Design considerations

5.1 Comparison with agricultural irrigation technologies

In Section 2.3.2 it is demonstrated that to achieve many of the various objectives, leachate recirculation should affect (i.e. distribute moisture to) as large a proportion of waste in the landfill as possible. The parallels with agricultural irrigation are obvious, and although there are many differences it is worth considering briefly the science and technology of a practice that has a much longer history than leachate recirculation.

Agricultural irrigation aims to apply water evenly over a targeted land area to create a uniform distribution of water over the root zone of the crop in question. The depth of the root zone will depend on the crop, and will vary from 150 mm for many vegetables and up to 1 m for crops like cotton and sugar cane. Some crops require 100% coverage of the growing area while others (e.g. in orchards) require less than 30–60% with irrigation occurring around individual plants. Compared with landfills, the limited vertical depth of irrigation is an obvious major difference.

The application rates are tailored to meet local evapotranspiration conditions. In hot areas of the world application rates of 8–10 mm per day are not uncommon. The aim is not to raise the soil moisture above the field capacity of soils since all such water above field capacity is considered to drain down rapidly by gravity into the water table and effectively is lost from the root zone of the crop. Similarly the soil moisture is not allowed to fall below a threshold level known as the permanent wilting point.

Whatever type of irrigation system is used, application is not applied continually. Typically water will be applied between 8 and 12 hours per day. This is partly to prevent roots becoming waterlogged and to let air enter the soil (not relevant to leachate recirculation), but also because experience has shown that continual application leads to falling infiltration rates (which is a finding that may be highly relevant).

5.1.1 Surface irrigation

Worldwide, approximately 80% of all agricultural irrigation is by surface application. Water is fed into the top end of a field, usually from open channels or from point discharges from a distribution pipe, and a ‘wave’ or continual flow of water is allowed to flow across the field. The technique is cheap and easy to use. Surface irrigation is unsuitable for very sandy soils and similar materials with high infiltration rates as it becomes very difficult to get the water to flow and cover the entire field with any sensible degree of uniformity. This is a technique that has very limited potential for use on landfills. Typical seepage rates from unlined irrigation through different types of material are shown in Table 5.1 for comparison with seepage rates achieved in landfills.

Table 5.1 Typical seepage losses in agricultural irrigation schemes.

Soil type	Seepage loss	
	l/s per 1000 m^2	l/m^2 per day (≡mm/day)
Impervious clay loam	0.8–1.2	100–150
Medium clay loam	1.2–1.7	150–230
Clay loam or silty soil	1.7–2.7	230–300
Gravel or sandy clay loam	2.7–3.5	300–450
Sandy loam	3.5–5.2	550–740
Sandy soil with gravel	6.4–8.6	740–900
Pervious gravelly soil	8.6–10.4	900–1800
Gravel with some earth	10.4–20.8	1000–1500

5.1.2 Subsurface irrigation

A typical subsurface irrigation installation would entail a buried drip tape. This may be a biodegradable plastic tube (flat or circular) with emitters (a device used to 'drip' or transfer water from a pipe or tube to the area to be irrigated) or simply perforations at regular intervals. This tape is installed prior to planting and remains in place until the crop is harvested. When the area is re-ploughed the drip tape is broken into smaller pieces and allowed to degrade naturally. In other installations, and particularly where non-biodegradable tapes are used, the drip tape may be designed to stay in place for several years before it is eventually removed. Typical emitter rates are of the order of 4 l/hour per emitter, and for perforated tapes typical emitter rates are of the order of 4 l/hour per metre length. Drip tapes are typically installed with a spacing of around 1 m.

It would be possible to achieve a layout for recirculation of landfill leachate similar to that for a subsurface irrigation system. However, in irrigation systems a single layer of drip tape is installed fairly close to the surface (typically 250 mm below the surface) and water is allowed to flow from emitters in the tape by gravity down into the root zone of a crop. In contrast in a landfill site if drip tape were being considered it may be necessary to install several layers of drip tape in a depth profile – particularly if the objective were to 'wet' the entire depth of landfill. Whereas in irrigation there has been considerable work and knowledge developed for the spacing of emitters based on a single layer in order to wet the soil profile, there has never been a need to install multiple rows of drip tape along a depth profile.

5.1.3 Filtration and chemical cleaning

Drip irrigation systems, such as those described above, require relatively clear and sediment free water. A rule of thumb in irrigation is that all particles greater than one-tenth of the diameter of emitter holes must be removed to prevent emitter plugging by ‘bridging’. A typical drip irrigation filtration system would probably need to remove particles of the order of 0.03–0.18 mm.

A second problem with drip irrigation, especially subsurface drip irrigation, is the blocking of emitters by algae and bacterial growth. In agricultural irrigation systems this is sometimes reduced and managed through chemical injection (e.g. chlorine).

Most leachate irrigation systems involve relatively large diameter pipework and screen or hole sizes. Direct clogging of pipework by suspended matter may therefore be less of an issue. Nevertheless, the suspended solid load in many leachates can be higher than in many water sources, and could lead to clogging of materials surrounding the pipe. Most leachates also have the potential to support biological growth and to precipitate inorganic solids when agitated or aerated. A number of examples are known where subsurface leachate irrigation systems have become blocked, by a combination of solid particulates, chemical precipitates and biological growth. It may therefore be necessary to consider the characteristics of individual leachates and the possible need for pre-treatment, to reduce the risks of clogging, particularly during the acetogenic phase.

5.2 Unsaturated flow theory

Leachate recirculation in most landfills is likely to occur predominantly through the unsaturated zone, and the main effect of this is to change the amount of water held by the waste. Unsaturated flow will occur until leachate reaches the water table of a saturated zone, be it at the base of the site or within a perched horizon within the body of the waste. The definition of the water table is the horizon in the waste where pore water pressures are zero relative to atmospheric pressure. This standard definition is complicated by the presence and effect of landfill gas, but may be ignored for the purpose of the current discussion. Pore-pressures will increase with depth in the saturated zone below the water table and will be negative above it as the result of surface tension effects resisting the vertical drainage of leachate towards the ‘water table’. Within this zone of negative pore-pressures the water content is generally reduced below saturation levels. Conventional models of seepage in partially saturated soils invoke a simple relationship between pore-pressure and water content. An example of the form of this relationship is given in Figure 5.1, and further details are included in the Appendix.

Figure 5.2 illustrates a landfill with a surface leachate injection layer some distance above a saturated basal drainage layer. Prior to any leachate injection, the pore-pressure at the base of the waste will be zero relative to atmospheric pressure and above this level the value of pore-pressure will become increasingly negative with elevation. The water content will also fall with elevation, following a relationship such as that shown in Figure 5.1, and as illustrated by curve A on Figure 5.2. If infiltration through a surface injection layer is now introduced the water content increases below the injection layer, and the distribution of water content changes from curve A to a transient distribution illustrated by curve B in Figure 5.2.

The rate of infiltration will sustain a new level of partial saturation at the upper boundary of the waste material. If the rate of infiltration is high enough the material will become fully saturated and the pore-pressure at the upper boundary will be zero. Infiltration rates higher than this will result in ponding and the pore-pressures at the upper boundary rising above zero.

The effect is to store a quantity of leachate in the waste material. At any point in time, the amount stored is the difference between the water contents represented by the distribution curves B and A.

Understanding this potential for transient storage of leachate may be important in the use of recirculation to buffer the seasonal variations in leachate flows to a landfill leachate treatment plant. Similarly the potential for changing the water content, upon which gas generation depends, offers a way of optimising the gas generation from the waste.

Figure 5.1 Example of the relationship between water content and pore-pressure.

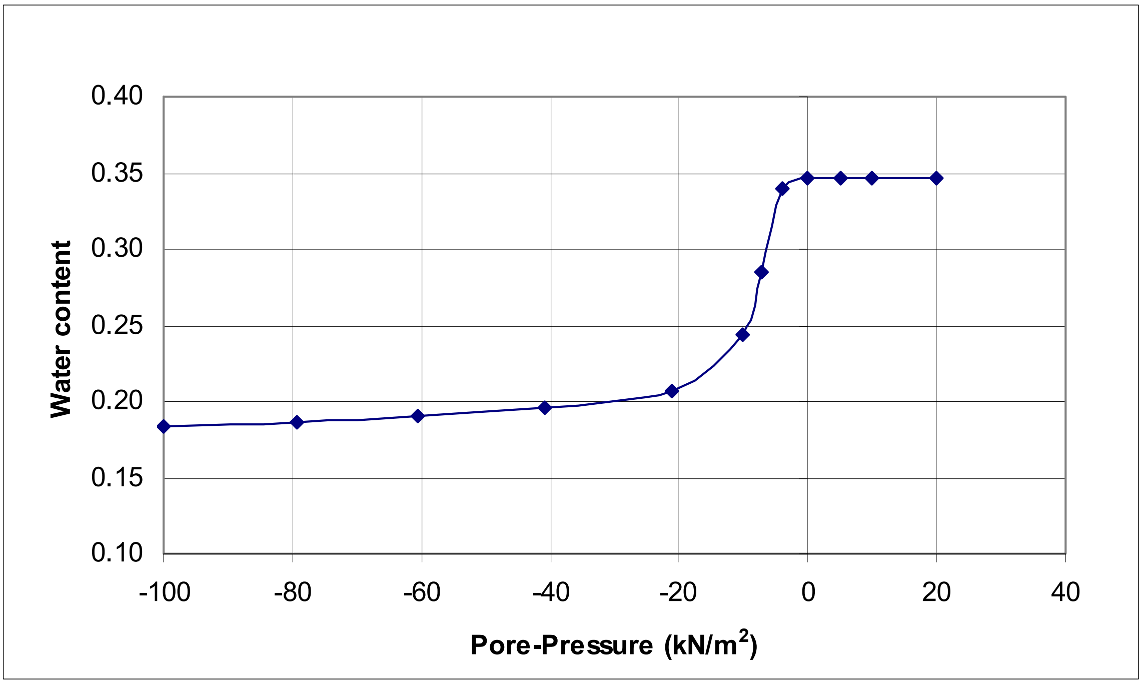
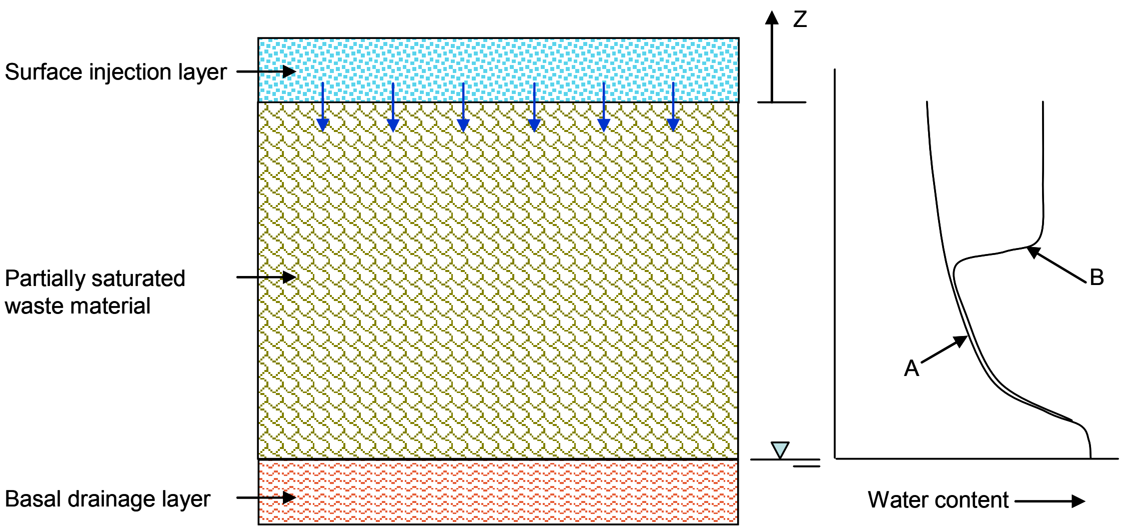


Figure 5.2 Transient water content following start up of recirculation.



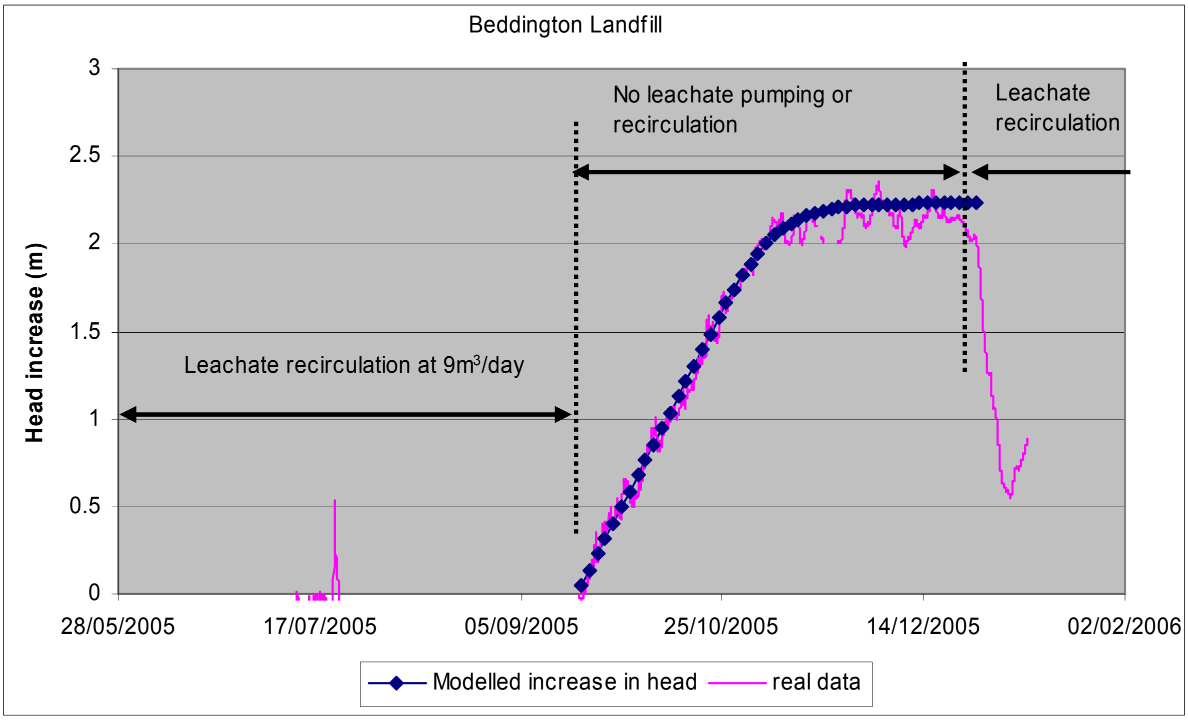
The extent to which increased or transient storage can be achieved, and water content changed, depends on the values of the physical parameters that determine the behaviour of seepage flow in the waste material. A simple conceptual model of the mechanism of saturation has been developed to represent the process analytically and may be used to calculate the order of magnitude of the extent of storage. Further details of this are provided in the Appendix. The potential application of the model is illustrated below, by reference to a case study of transient storage during recirculation.

A cell at the Beddington landfill, Croydon, has been the subject of a Landfill Tax Credit Scheme funded research project between July 2000 and January 2006 into the hydraulic response of landfills to infiltration events (Knox and Shaw 2006a, 2006b). A ~1 ha clay capped test cell contains a gravel drainage layer across the whole base of the site into which 20 vibrating wire piezometers were installed to monitor leachate head. The study, among other findings, demonstrated excellent hydraulic continuity across the whole drainage blanket and the rapid response in hydraulic heads both to rainfall infiltration events, and to leachate abstraction. A 30-m long leachate injection trench was installed in the top of waste below the cap and used for leachate recirculation throughout most of 2005, where all the leachate pumped out of the drainage system was reinjected into the trench. It is estimated that during the late summer 2005, leachate recirculation rates through the system had stabilised at a steady state rate of approximately 9 m^3/day, and low leachate heads were maintained across the whole drainage system.

On 20 September leachate pumping (and recirculation) was stopped, in a planned exercise to monitor the impact on leachate levels. Over the following 2 months leachate heads rose by 2 m and then stabilised at 2.2 m above levels that had been maintained during recirculation (Figure 5.3). Leachate recirculation restarted in late December 2005, resulting in a rapid reduction in leachate levels in the drainage blanket. The hypothesis is that the increase in levels was caused by the draining down of leachate held in transit within the landfill. An analytical model based on the theory summarised above and detailed in the Appendix has been successfully applied to this situation and accurately predicts the increase in heads monitored. Figure 5.3 shows an excellent fit between actual and modelled behaviour, giving confidence to the theory and its application developed in the Appendix.

The worked example shows that the use of this type of analytical model can not only be used to predict the potential increase in leachate head following the cessation of leachate recirculation, but it can also be used to calculate the volume of transient leachate stored in a landfill during recirculation and how leachate recirculation could be used to buffer the seasonal variations in leachate flows to a landfill leachate treatment plant.

Figure 5.3 Actual and modelled increase in leachate head in a basal drainage system following cessation of leachate recirculation.



5.3 Design of leachate injection infrastructure

A number of researchers have started to consider the design of leachate injection or recirculation infrastructure based on saturated and unsaturated flow theory through wastes. The designs have concentrated on the potential spacing of, for example, horizontal injection trenches or wells to achieve an optimum 'wetting' of the waste, and on the effect of injection pressure.

The main controls over the movement of leachate through the waste can be summarised as follows:

- hydraulic properties of wastes (both saturated and unsaturated)
- anisotropy
- heterogeneity
- infrastructure: location, injection parameters (i.e. boundary conditions)

Although many researchers have developed their own numerical models, there are commercially available software programs that can be used to simulate basic saturated and unsaturated flow.

SUTRA is the US Geological Survey's saturated–unsaturated flow and transport model, which can model unsaturated flow in two dimensions. McCreanor and Reinhart (1999, 2000) used SUTRA to model leachate movement in a leachate recirculating landfill, and considered both vertical wells (1999) and horizontal trenches (1999, 2000). The work on horizontal trenches was more comprehensive and considered the effect of permeability anisotropy and also heterogeneity. A variety of scenarios were considered based around a maximum saturated hydraulic conductivity of 1×10^{-5} to 1×10^{-6} m/s. Assuming a (relatively high) isotropic saturated hydraulic conductivity of 1×10^{-5} m/s, the effect of injection rates between 2 and 8 m^3/day per metre of injection trench were considered on the lateral spreading of the injected leachate. An approximately linear relationship was produced, with a lateral spread of 10 m at an injection rate of 8 m^3/day per metre. Not surprisingly, when anisotropic conditions were simulated, with a horizontal permeability ten times higher than the vertical, much larger lateral spreads in moisture distribution were predicted.

Haydar and Khire (2005) considered design issues around the use of horizontal injection trenches in waste materials by applying the HYDRUS-2d computer model that simulates both saturated and unsaturated flow in porous media. The study considered a homogeneous waste, with a saturated hydraulic conductivity that was 10^{-5}, 10^{-6} or 10^{-7} m/s, and considered injection pressures up to a maximum of 5 m of leachate head. Unsaturated flow properties were based on the Van Genuchten representation of unsaturated flow. Predicted steady state leachate flux from an individual trench was directly proportional to waste permeability: a waste permeability of 1 x 10^{-6} m/s resulted in a flux of 0.5 m^3/day per metre of trench for a 1 m applied leachate head (or 5 m^3/day per metre of trench at a permeability of 1 x 10^{-5} m/s, which corresponds well with the modelling results of McCreanor and Reinhart above). Increasing the injection pressure resulted in a non-linear increase in flux, and a limited increase in the horizontal distance of wetting. The paper considered the impact of horizontal and vertical drain spacing on wetting efficiency and, for typical landfill conditions, concluded that a single layer of horizontal drains should be spaced at a distance of approximately 10 m, which could be increased to 20 m if the layer was offset against a higher or lower layer with similar spacings but with a staggered offset.

Khire and Haydar (2003) also considered the operation of a granular drainage blanket in comparison to a series of horizontal trenches. The work again used HYDRUS-2d, assumed isotropic landfill conditions and considered steady state conditions. Trenches spaced at 15 m centres were predicted to yield between 60 and 90% of the values obtained from the drainage blanket.

A shortcoming with the above type of approach is that although it can provide approximate guidance on design issues, the problem of waste heterogeneity and leachate short-circuiting is not addressed.

McCreanor and Reinhart (2000) investigated (using SUTRA) the impact of both waste anisotropy and waste heterogeneity on leachate recirculation from horizontal trenches. Heterogeneity was investigated by allocating variable hydraulic conductivities to each 50 x 50 cm element in a modelled cross-section. Hydraulic conductivities were assigned using random numbers and probability density functions, with either normal distributions (i.e. there was a high probability that the hydraulic conductivity of each element was close to an average), or exponentially increasing (higher probability of high hydraulic conductivity areas) or exponentially decreasing distributions.

The modelling clearly demonstrated the impact of spatial variations in hydraulic conductivity on moisture distribution. However, determining the actual distribution of permeability throughout a landfill is largely a matter of conjecture, although the comparison of the modelling work with field observation pointed to either normal or exponentially increasing probability functions (which allows short-circuiting) as being potentially valid.

McCreanor and Reinhart (1999) modelled (using SUTRA) the operation of vertical injection wells in a homogeneous landfill with a saturated hydraulic conductivity of 1 x 10^{-5} m/s. Flow rates of between 0.2 and 0.8 m^3/day were applied to a 9-m screened horizon in a modelled well, over a period up to 40 days. The results concluded that vertical wells were inefficient at wetting the upper part of the landfill, and this was related to an imposed modelling constraint where the flux out of a vertical section of the well was increased with depth. It is well known that hydraulic conductivity is likely to decrease with increasing stress and hence depth in a landfill (Powrie and Beaven 1999) and in recent field-scale borehole permeameter tests Jain *et al*. (2006) demonstrated a significant reduction in permeability with depth. Consequently, it might be expected that the flux out of a unit length of well should decrease with depth. However, Al-Thani *et al*. (2004) in detailed three-dimensional modelling of the performance of a leachate pumping well, where the hydraulic conductivity of the landfill decreased with depth, concluded that in many circumstances the flux flowing into a unit length of well increased with depth.

Khire and Mukherjee (2007) have also considered the performance of vertical wells in a homogeneous and isotropic 20 m deep landfill using HYDRUS-2d. A variety of factors were considered, the most important of which were the saturated hydraulic conductivity of the waste (10^{-5},10^{-6}, 10^{-7} m/s), the depth of the well, the height above the landfill base that the well terminated (2.5 to 14.5 m), and injection pressure and rate. These variables were also considered alongside the design of the basal leachate drainage layer (nature/permeability of drainage material, gradient on base, collection pipe spacing etc) to investigate the impact of leachate recirculation on maximum leachate head. The modelling demonstrated a direct relationship between waste permeability, injection pressure/rate and wetted width. For a waste with a hydraulic conductivity of 10^{-6} m/s, a 3 m screened well developed a wetted width of 8 m at an injection rate of 5 m^3/day with an average injection pressure 4 m water head. Khire and Mukherjee (2007) noted that for a given hydraulic conductivity the wetted width increases with increasing injection rate. Nomograms are provided indicating wetted widths that go up to 20 m or more. However, to obtain a wetted width much over 10 m, unrealistically high injection pressures are required whatever the hydraulic conductivity and flow rate.

Although the general modelling tools are available to aid in the design of leachate injection infrastructure, their appropriate use is reliant on accurate information on the hydrogeological properties of landfills. More information is required, in particular on waste heterogeneity, layering and the unsaturated flow characteristics of wastes. However, the modelling tools are good at demonstrating what can be achieved and can elucidate the mechanisms occurring during recirculation.

6 Observations on operational issues

The following potential operational issues have been identified:

- infrastructure design
- clogging/reduction in performance of injection infrastructure
- flooding of gas wells
- daily cover
- effects of settlement
- clogging of basal drainage layer
- obtaining sufficient volumes to recirculate
- slope instability

Some of the operational issues identified here also have environmental implications (see Table 8.1).

6.1 Performance of different types of recirculation infrastructure

Performance of different types of leachate injection infrastructure is considered in Sections 6.1.1 to 6.1.5, with application rates summarised in Table 6.1.

Two different application rates need to be considered:

- The first is the infrastructure injection rate. This relates to some physical measure of the injection system. For surface application and injection into drainage pads, the area of application is chosen as the reference dimension. Application rates are normalised to litre per square metre per day ($l/m^2/day$). Many horizontal injection pipes are laid in trenches, and it would usually be impractical to calculate the basal and side area of the trenches, so application rates for this type of system are therefore normalised to litres per linear metre of pipe per day (l/m/day). The same approach has been taken with injection wells, where the length of well screen is taken as the reference. Occasionally, it is feasible to give infrastructure injection rates based on both area and length of injection system. This would normally be appropriate for closely spaced systems where even wetting between linear infrastructure is highly likely. An example of this would be band drains.
- The second measure is the areal application rate. This is the rate when averaged over the whole of the area assessed as being affected by the recirculation activity.

6.1.1 Low pressure surface application methods

Low pressure surface application methods are taken to include surface ponds, open trenches and irrigation at the tipping face using a bowser and other such methods.

Application rates of 5–8 $l/m^2/day$ were obtained in large-scale trials using surface infiltration ponds in the USA. These application rates are more than an order of magnitude lower than the potential agricultural irrigation rate (of 100–150 $l/m^2/day$) into a low permeability clay loam and may indicate clogging or blinding of the base of the pond. On purely theoretical considerations, and in the absence of any low permeability cover, then maximum infiltration rates into waste with a permeability of between 10^{-5} and 10^{-7} m/s would be between 864 and 8.6 $l/m^2/day$.

Data on irrigation at the tipping face suggest that application rates of between 10 and 40 m^3/day are achievable in practice (this review). If an assumption is made that the average size of the tipping face over which irrigation takes place is 1000 m^2 (50 x 20 m), then an application rate of between 10 and 40 $l/m^2/day$ can be calculated. More aggressive leachate irrigation of the tipping face has been practised in the USA (Thiel 2005) where a large spray cannon was used to irrigate a 0.6 ha tipping face and achieved rates of up to 66 $l/m^2/day$.

6.1.2 Horizontal trenches and pipes

A wide variety of designs are included in this section, and include shallow (i.e. just below the cap) trenches (with or without perforated pipes) and more deep-seated systems either involving ‘spiders’ running off a central access shaft or sub-parallel horizontal pipes or trenches.

Within our UK survey, operators reported mixed results with this type of system, with many suggesting that there were difficulties maintaining hydraulic access to the buried infrastructure, leading to long-term performance issues. However, there were many other examples of trenches and pipework accepting large volumes of leachate. Data from one site with a single 30 m long tyre-filled trench achieved injection rates of 830 l/m/day. In a recirculation hydraulics study at one of the Brogborough test cells (Mouchel Consulting Ltd, 2001) a similar sub-cap trench 20-m long received ~1000 m^3 leachate in one year, an average rate of 137 l/m/day, peaking at 250 l/m/day. As flows were at all times constrained by availability of leachate from an abstraction well, it is almost certain that higher injection rates could have been maintained.

Another UK operator reported recirculating 35,000 $m^3/year$ into a site. Insufficient details are available to calculate an injection rate per linear metre of pipe.

Short-term injection rates of 600 l/m/day were reported by Reinhart, and this relates to the theoretical injection rates that both McCreanor and Reinhart (1999, 2000) and Haydar and Khire (2005) calculated. The relationship between injection pressure into horizontal trenches and injection rates have been demonstrated in the field by Reinhart (1996) and Townsend and Miller (1998) and theoretically by Haydar and Khire (2005), although the field work did show a reduction in rate over time.

Reported long-term injection rates that have been achieved in the field are considerably lower than the short-term injection rates quoted above, and range from 7 to 70 l/m/day. This is certainly related in part to the systems not being operated at full capacity, but it is difficult to make many statements about how near to full capacity the various schemes were.

The site with the highest long-term areal rate applied via a linear system is the XL bioreactor cell at Yolo County, USA (Yazdani *et al*. 2006), where only green waste was used as intermediate daily cover. Their system achieved an areal rate of 13 m^3/ha/day, at linear infrastructure rates of 12–70 l/m/day. The high areal rate at such modest linear rates was achieved by having a relatively close spacing of pipes (between 8 and 12 m).

The spacing of trenches and pipes varied between as little as 8 m horizontally, up to 60 m or more. However, many sites had used spacings of between 20 and 30 m. Work undertaken at the Drambon landfill, France, on optimum trench spacing indicated that the mean zone of influence was perhaps of the order of 15 m laterally. Fitting of data from a UK injection trench to a one-dimensional flow model (see Appendix) achieved a good fit by assuming a wetting zone 10 m on either side of a 30-m long trench. A theoretical analysis by Khire and Mukherjee (2007) indicated that for isotropic waste it was difficult to achieve wetting widths much over 10 m without imposing unrealistically high injection pressures, which perhaps indicates that the role of waste anisotropy and heterogeneity is an important factor. Where vertical spacing of injection trenches has been used, 6 m is the minimum reported spacing.

6.1.3 Pads and drainage blankets

Subsurface pads are taken to be rectangular pits (or areas) filled with drainage material, often whole or shredded tyres.

Within the UK survey, there were a number of examples of injection systems based on small-scale pits (~1 x 1 m) that had failed to perform well, and the impression was obtained that larger pads (e.g. 50 x 50 m) performed considerably better. Haydar and Khire (2007) also investigated the use of a 60 x 9 m ‘permeable blanket’ consisting of a 0.15 m thick layer of crushed glass aggregate, and injected 3200 m^3 over a period of 7 months. This gives a long-term infrastructure injection rate of 28 l/m^2/day, which is very similar to the performance of the tyre-filled pad identified in this study (24 l/m^2/day). Short-term injection rates were possibly as high as 1440 l/m^2/day. In contrast to some UK experiences, small pads were used very successfully at Yolo County, where 13 tyre-filled pits at 8 m spacings were used to inject 8000 m^3 leachate into the ~8000 tonne test cell over a 9-year period. The long-term infrastructure injection rate was approximately 19 l/m^2/day, assuming each pad to have an area of 10 m^2.

Recently, Khire and Haydar (2007) have also reported on the use of a ‘blanket’ of 7.5-mm thick geocomposite material as a leachate injection layer. An area of landfill 12 x 34 m was covered with the geocomposite and fed via a central 12 m long perforated pipe. Short-term injection tests gave infrastructure injection rates of between 705 and 1765 l/m^2/day for injection pressures of between 2 and 8 m head.

6.1.4 Vertical injection wells

Although within our study of UK practice, most operators said they have used vertical wells for leachate recirculation (often successfully), there were very few quantitative data on their performance. This appears to be a position reflected in the international literature, with the notable exception of the research being undertaken at the New River Regional Landfill (NRRL), Florida, and at the La Vergne landfill, France. Within both these sites the use of vertical wells has achieved areal recirculation rates of approximately 8 m^3/ha/day. This compares favourably with the rates achieved by trenches and horizontal pipework distribution systems (Table 6.1). When injection rates are related to well screen length, long-term infrastructure injection rates of between 50 and 90 l/m/day were easily achieved. Detailed investigations at NRRL indicated shorter term, but nevertheless steady state, injection rates that were between 144 and 700 l/m/day. Jain *et al*. 2006 also reported that injection tests into shallow wells at NRRL often suffered from short-circuiting to side slopes, gravel-filled gas collection trenches or the surface itself. The very high injection rates of 6875 l/m/day reported for one set of shallow wells in this study may also have been influenced by some kind of preferential flow to a nearby gas well. High pressure injection (~30 m water head) into a set of 12 moveable pin wells achieved short-term injection rates of between 4000 and 6000 l/m/day, and appeared to be a good way of increasing the water content of waste in advance of overtipping.

The research at La Vergne landfill (e.g. Skhiri *et al*. 2006) investigated the radius of influence of injection wells discharging into the unsaturated zone and concluded that, following a year of injection, the radius of influence was between 5 and 10 m. This result can be supported by the modelling work of both McCreanor and Reinhart (1999) and Khire and Mukherjee (2007).

6.1.5 Band drains

Band drains are really a form of vertical wells, but are considered separately here as the very close spacing of the individual 'wells' make them a special case. Covering the surface of the band drains with a permeable layer means that the system has the added advantages of the pad type approach.

The system implemented by one UK operator involved geotextile drainage 'socks' installed at 1 m centres on a 40 x 40 m grid, to alternating depths of 5, 10 and 15 m. The top surface of the 'socks' is then overlain by a bed of drainage material to distribute injected leachate evenly over the whole area. In one case where the top drainage layer was not included in the design, the system did not work.

The example of the band drain identified in this study involved the injection of 200 m^3/day into the system over a period of 45 days. It is estimated that there was 18,000 linear metres of drainage 'sock' in the system, which means that an infrastructure injection rate of 11 l/m/day is calculated. Compared to the injection rates for wells, this is relatively low, and helps explain why the system has been highly successful. The volume of waste encapsulated by the band drain system is estimated to be 24,000 m^3. A total of 9000 m^3 was injected over a 45-day period, which (assuming an initial waste density of 1 t/m^3) represents a water addition of 375 l/t. This amount of water could not have been held locally either within the confines of the injection system or just outside, and there must have been a bulk movement away from the zone of injection.

6.2 Clogging/reduction in performance of injection infrastructure

All operators reported problems with clogging or poor hydraulic performance of various types of infrastructure, many exhibiting deterioration over time. Few leachate flow and quality data are available. In the Brogborough test Cell 2 recirculation experiment, the first vertical access pipe clogged while the leachate was still acetogenic, and had to be replaced by a newly drilled access pipe. The hydraulic performance data quoted for the injection trench in Section 6.1 and Table 6.1 occurred after the leachate had become methanogenic. Similar problems occurred at another UK site, with an access pipe into a sub-cap injection trench. At the Yolo County XL bioreactor cell, clogging of horizontal injection pipes occurred initially, reportedly due to the introduction of 'high pH liquids'. Remediation was achieved successfully using citric acid and no subsequent problems occurred. At the CSWMC Delaware landfill (see Section 4.4) vertical wells filled with pea gravel clogged very quickly and were replaced with large diameter concrete rings, filled with large stone.

One UK operator reported 'silt' accumulation in radial 'spider' trenches. 'Silt' accumulating in the open trench at another operator's site was periodically cleaned out to prevent a reduction in performance due to clogging. It was believed the silt was washed in from the side of the trench rather than precipitating, but there is no analysis or other information to confirm its origin. Band drains and large volume tyre pads have not exhibited the effects of clogging so far.

This is clearly an important practical issue: clogging over a period of just a few weeks appears common, when the injected leachate is acetogenic. When the leachate is methanogenic, systems have operated for a period of up to several years without apparently clogging. However, quantitative data to support this are rare and the long-term (>5 years) loss of function, if any, is not known. We have found no known work describing pre-treatment specifically to address protection of injection infrastructure. It would appear still to be a significant challenge to accommodate recirculation during the acetogenic period using subsurface systems.

6.3 Flooding of gas wells and other subsurface infrastructure

There was widespread reporting within our UK survey of instances where leachate recirculation had led to the filling up of nearby gas wells. One operator had experienced problems with the interaction of leachate and gas flows, mainly in band drains. To counter this, leachate injection is controlled using a typical routine of 1 week recirculation, 1 week standoff and 2 weeks gas extraction. An operator with a grid of specially installed dual-purpose pin wells reported using one row (out of five) for gas extraction and the other four for leachate injection, rotating on a weekly basis.

Problems referred to by Thiel (2005), from surface application by water cannon included:

> *Extensive flooding of gas wells occurred as a result of leachate irrigation. This required the operator to set up a large air compressor needed to run air-diaphragm pumps that would dewater the gas wells. Flooded gas well greatly reduce the gas collection efficiency which can lead to odor problems.*
>
> *Significant amounts of leachate get into gas collection suction lines, especially from horizontal wells, due to the well-field suction. This caused surging of gas pressures, and uneven gas delivery to the cogeneration engines*.

Localised flooding of nearby gas wells is clearly a common risk during recirculation. An alternating mode of operation of leachate injection facilities appears to be the best approach to overcome these problems and is used routinely by several operators interviewed during this study, as well as being referred to in the literature.

Table 6.1 Summary of reported and potential application rates for different types of injection infrastructure.

System type	Sub-set	Infrastructure application rate	Areal application rate (m^3/ha/day)	Applied head (m)	Note	Scale of study	Reference
Low pressure surface applications	Infiltration lagoons	5.2–7.9 l/m^2/day	2.5	Minimal		Field	Reinhart 1996 Townsend et al. 1995
	Irrigation at tipping face	10 to 40 l/m^2/day 34 – 66 l/m^2/day		N/A	From bowsers Large spray cannon	Field	This study Thiel 2005
	Spray irrigation	No information		N/A	Reported use in UK and USA (see Table 4.1)		This study Morris *et al*. 2003
	Agriculture irrigation into clayey loams	100–150 l/m^2/day		N/A		Agricultural practice	This study
	Maximum infiltration into waste with hydraulic conductivity of between 10^{-5} and 10^{-7} m/s	864 and 8.6 l/m^2/day		N/A	Assumes no low permeability cover, and takes no account of impact of gas generation	Theoretical	This study
Trenches and horizontal pipes	Tyre-filled trench	830 l/m/day			Tyre filled trench 30 x 3 x 1 m	Field	This study
	Gravel-filled trench	137 l/m/day		0 – 3m	Brogborough test cell 2. Gravel filled trench 20 x 0.9 x 1 m	Field	Mouchel Consulting Ltd 2001
	Deep (~5–7 m deep) tyre filled trench	205–274 l/m/day			Liquid injection trenches – 130,000 m^3 in 1300 m of trench in 1 month	Field	This study
	Tyre-chip-filled trenches with pipes	600 l/m/day short term 290–380 l/m/day per metre of applied head 29 l/m/day long term	4.7	0–15	Alachua County, Florida 1738 linear metres of trenches: 11 trenches at 15 m lateral and 6 m vertical spacing	Field	Reinhart 1996, Townsend *et al*. 1995[1]
	Perforated pipes in gravel-filled trenches	10 l/m/day	1.1		Pecan Row Landfill, South Georgia 30 m spacing off three pressurised force mains	Field	Reinhart 1996
	32 mm HDPE pipe	12–70 l/m/day	11–13		Yolo County Project XL Bioreactor Horizontal pipes with 2.3-mm hole every 6 m. Spacing between 8 and 12 m	Field	Yazdani *et al*. 2006
	75 mm OD PVC pipe in gravel-filled trenches	10 l/m/day	2.4–6.1		Busta 5 x 130 m long trenches at 25 m spacings	Field	Barina *et al.* 2001, 2003, Barina 2005

System type	Sub-set	Infrastructure application rate	Areal application rate (m^3/ha/day)	Applied head (m)	Note	Scale of study	Reference
	75 mm OD PVC pipe in gravel filled trenches	8 l/m/day	5.5		Drambon 5 x 70 m horizontal trenches	Field	Barina, 2005
	Perforated pipes in injection trenches	7 l/m/day	9		Landgraaf Injection trenches 5 x 35 m at mid height of cell and 6 x ~60 m at 90° orientation under cap	Field	Woelders *et al.* 2005
	Modelled injection trenches	2000–8000 l/m/day 200–800 l/m/day			For K = $1x10^{-5}$ m/s For K = $1x10^{-6}$ m/s	Model	McCreanor and Reinhart 1999, 2000
	Modelled injection trenches	30–130 l/m/day 3000–13,000 l/m/day		0–5 m	For K = $1x10^{-7}$ m/s and head = 0–5 m For K = $1x10^{-5}$ m/s and head = 0–5 m	Model	Haydar and Khire 2005
Pads	50 x 50 x 2 m tyre-filled pad	24 l/m^2/day		N/A	9000 m^3 over 5 months	Field	This study
	13 tyre-filled pits at 8 m spacings	19 l/m^2/day	27	N/A	Yolo County test cells -8000 m^3 injected over 9 year period	Field	Augenstein *et al*. 2005b
	60 x 9 x 0.15 m blanket of crushed recycled glass	28 l/m^2/day (long term) 1440 l/m^2/day (short term)			3200 m^3 injected over 7-month period	Field and model	Haydar and Khire 2007
	408m^2 geocomposite drainage layer	21 l/m^2/day (long term) 705–1765 l/m^2/day (short term)	N/A	2–8 m	Short-term tests (over 7 months) undertaken on a 12 x 34 m geocomposite blanket fed by a central 12 m perforated pipe	Field	Khire and Haydar 2007
Wells	4 shallow wells 2 m into upper surface of waste	6875 l/m/day		3 m	In operation for over a year. Drilled at 500 mm diameter	Field	This study
	18 injection wells at 30 m spacing	90 l/m/day	~8.9		La Vergne – Some wells had split response zones	Field	Bureau *et al.* 2005
	134 vertical wells in 45 clusters at 15 m spacing	50 l/m/day (long term) 144–700 l/m/day (steady state)	8.4	1–15	New River Regional Landfill, Florida Bioreactor	Field	http://bioreactor.org/nrrl Jain *et al*. 2006
	12 shallow pin wells at a spacing of 10–15 m	~4000–6000 l/m/day (assumed) 110–160 l/m^2/day	11.7	Up to 30 m	Assumer 24 m of well screen (assume 2 m screen per pin). Injection rate 100–145 m^3/day A: 900 m^2	Field	Reinhart 1996

System type	Sub-set	Infrastructure application rate	Areal application rate (m^3/ha/day)	Applied head (m)	Note	Scale of study	Reference
	Modelled injection wells	22–89 l/m/day			Saturated hydraulic conductivity of $1x10^{-5}$ m/s	Model	McCreanor and Reinhart 1999
	Modelled injection wells	Very wide range predicted		Various	Saturated hydraulic conductivity of 10^{-5},10^{-6}, 10^{-7} m/s	Model	Khire and Mukherjee 2007
Pin wells and band drains	Band drains at 1 m centres on 40 x 40 m grid	11 l/m/day 125 l/m^2/day	Not known		Each band taken to alternating depths of 5, 10 and 15 m. ~18,000 m drain in 40 x 40 m grid. Q=200 m^3/day over 45 days	Field	This study

Conversion factors: 1 l/m^2/day ≡ 1 mm/day
1 m^3/ha/day ≡ 0.1 mm/day

6.4 Daily cover

Low permeability cover was widely noted as causing problems – it inhibits vertical flow, encourages horizontal movement and creates bigger risk of flooding gas infrastructure and causing lateral surface seepages. One UK operator had experienced a line of surface seepages corresponding exactly to the position of a previous layer of cover. Another bemoaned the insistence of regulators, who in one case required cover to the extent of 40% of the airspace. In the Yolo County study, the use of green waste as daily cover was successful in avoiding these problems. However, problems did occur when they were required to use more conventional cover.

If recirculation becomes more widespread, and recirculation flow rates increase (e.g. for flushing), the issue of cover will become more and more problematic. There is clearly a challenge to achieve the objectives of daily cover, but using methods and materials that do not cause hydraulic barriers.

6.5 Effects of settlement

Many operators reported some problems with failure of pipework in horizontal pipes and radials, attributed to settlement. However the cause of failure of pipework at depth in landfill is difficult to establish with certainty. Settlement on most landfills will be large, and is likely to be locally increased in the zones around injection systems. Drainage systems will need to be designed to accommodate this. Some types of infrastructure may be better able to accommodate settlement than others; for example, pads, band drains and surface applications may accommodate settlement better than some horizontal pipe systems.

6.6 Clogging of basal drainage layer

No evidence of increased clogging as a consequence of recirculation was reported by any operator. However, Environment Agency staff have reported that this has happened. It has also been suggested that the practice of maintaining drainage layers in an unsaturated condition may be a more important cause of the clogging of basal layers. Regardless of the cause, consideration may need to be given to how any gradual loss of porosity or transmissivity from a drainage layer could be monitored during normal operation of a landfill.

6.7 Obtaining sufficient volumes to recirculate

Some operators reported running out of leachate to recirculate when trying to increase gas generation. This matches US experience, where importation of liquids has been necessary to provide the moisture needed to stimulate gas production.

It should be straightforward, via a conceptual process design, to indicate the quantities of liquid needed for this purpose and to assess whether addition of external water is necessary. It could then be integrated with the site water balance and leachate management plan.

6.8 Slope instability

No instances of slope stability problems relating to leachate recirculation were reported by the operators who took part in the survey. Three operators raised this issue and said that they would not operate a leachate injection system near the edge of the site (a 30-m ‘no-go’ zone was suggested by one). However, the adverse effects of a raised pore-pressure on slope stability in soils are very well known in soil mechanics, and as a potential hazard this must also be expected in a waste landfill.

Some instances of catastrophic slope failure have occurred, mainly (though not exclusively) at landfills in tropical locations, following extreme rainfall events. Slope failure tends to occur where pore-pressures have become high and a significant slope exists. The most severe risk of such events in the UK would probably occur if recirculation were undertaken at high rates and/or where higher pore-pressures already existed due to historical accumulation of leachate. They could also be exacerbated by high pressure injection because this could lead to high pore-pressures.

Consideration of slope failure risk would need to include the back slopes of steep-side sites, as well as front slopes. For example, excessive irrigation close to a smooth geomembrane-covered side wall could increase the risk of slope failure.

7 Observations on environmental issues

The following potential environmental concerns have been identified in connection with leachate recirculation:

- odours and uncontrolled gas release/air ingress;
- adverse impact on leachate quality;
- increased head on liner systems;
- perching/surface outbreaks;
- surface water contamination;
- short-circuiting;
- interaction of leachate and gas.

Some of the above environmental issues also have operational implications (see summary in Table 8.1).

The extent to which these have been troublesome in practice will now be assessed with reference to information and data from the survey of landfill operators, and from the literature.

7.1 Odours and uncontrolled gas release/air ingress

A number of operators discussed experiences relating to odour problems. Recirculation had been stopped at some sites by the Environment Agency because of this. The schemes that seemed to produce problems were injection into open trenches or soakaways where the surface of the liquid was exposed directly to the atmosphere. The injection of leachate into sealed wells or injection infrastructure was ‘proposed’ by one operator to prevent odour problems. The degree to which exposed leachate is a potential source of odour will depend on the strength of the leachate and its inherent burden of odorous compounds. Leachate recirculation at one site created a problem with H_2S odours, attributed to recirculating through deposits of sulphate-rich industrial waste.

Irrigation (e.g. from bowsers) at the tip face has been prevented at some sites by the Environment Agency (the operator reported that the reasons for this were not made clear, although bio-aerosols were quoted as the reason at one site). This method is, however, widely practised and is known to be incorporated into at least one Working Plan. No odour problems were reported from this method in our survey, though it is not clear whether this is because operators only select weaker leachates for irrigation.

Odours, gas release and the potential for air ingress were identified as significant issues during the installation of band drains, due to the rapid placement of densely spaced bores. The operator recommended covering the band drains with additional waste as soon as they are installed, as a necessary measure to control the problem.

Air ingress via uncapped injection structures, leading to subsurface fires, was also identified as a risk, though no specific instances of this were reported by operators.

7.2 Adverse impact on leachate quality

A very small number of instances were reported where operators thought there was an adverse impact (i.e. leachate concentrations increased). However, there do not seem to be data to support this perception. At least as many operators thought from their own experiences that there was no detectable impact on leachate quality. Some anecdotal evidence has noted short-lived flushes of acetogenic leachate reaching the site base on uncapped areas, following extreme rainfall events, and it is possible that the same could occur with high rates of recirculation.

7.3 Increased head on liner systems

The review has found no evidence to support the common concern that leachate recirculation would increase the head on liner systems. Available data suggest that for a given volume of leachate within the landfill recirculation will keep a significant amount of leachate ‘in transit’ within the waste so that it does not add to the pore-pressure in the basal drainage system. This was also a conclusion from a US review of leachate recirculation (Benson *et al*. 2007). One operator provided a monitored example of recirculation lowering leachate heads at the base of the landfill, and some regulators have reported heads rising when recirculation is stopped. Knox and Shaw (2006a, 2006b) give an example in which leachate heads in the basal drainage system rose by 2.1 m in 48 days when the leachate ‘in transit’ was allowed to collect there, following interruption of leachate extraction and recirculation.

7.4 Perching/surface outbreaks

Re-emergence of injected leachate may give rise to problems from odour from the exposed liquid or to contamination of adjoining ground or surface water. Most UK operators reported some instances of perching or surface outbreaks, but none of the instances reported led to any environmental harm. One operator reported an increased potential for perching, resulting from recirculation at the tip face irrigation and into an under cap system. A similar problem of perched leachate was observed at another site, where injection into an extensive network of pipes (15 km installed for gas scavenging) was required to overcome the problem.

Injection into sub-cap infrastructure where the receiving capacity was exceeded led at one site to the overflowing of leachate at the surface. One operator solved this problem with manual controls, whereas other operators felt that more sophisticated control systems with fail-safe mechanisms were necessary to reduce risk of surface outbreaks etc (e.g. from a burst pipe).

Injection into a pipe/trench system beneath a lapped synthetic cap led to a surface outbreak. The pipes were erroneously laid on a shallow gradient; this led the leachate to the lowest point, where localised heads built up under the cap. Similar systems laid accurately level along the contour under a clay cap resulted in fewer (if any) problems.

An outbreak of leachate as a spring line above an old restoration layer was reported at one site and a further leachate breakout 30 m from an injection trench at another.

Surface breakouts were also experienced in some overseas experiments described in the literature (Section 4), especially where high injection pressures were used.

Avoiding surface breakouts requires consideration of several factors:

- The lateral zone of influence of most types of infrastructure appears to be typically of the order of 5 to 10 m, with a maximum of ~15 m. Therefore a lateral exclusion zone of 20 m or more from the edge of a slope should help to minimise the risk.
- The exclusion zone may have to be greater where pressure injection is being undertaken. The high pressure may permanently open up new permeable pathways.
- Low permeability daily cover clearly increases the risk of surface breakouts. Consideration might therefore be given to using a permeable material, particularly at the edges of slopes.

7.5 Surface water contamination

Pipelines carrying leachate across restored surfaces to injection points present a potential risk to surface water in the event of leak. No instances of surface water contamination as a result of leachate recirculation were reported in this review. The potential for surface water contamination is a factor that should be considered explicitly in any recirculation scheme. It should be controllable through good system design and management.

7.6 Short-circuiting

There was no evidence that short-circuiting of leachate was a problem in our UK survey. A leachate monitoring well 30 m from a band drain accepting 200 m^3/day showed no evidence of short-circuiting, or lateral movement of leachate over that distance. One operator was concerned that drainage media extending up the side walls could lead to short-circuiting routes, and another about the possibility of short-circuiting around the waste–cap interface.

In overseas studies, high pressure injection led to hydro-fracturing and consequent short-circuiting to the base of the cell in one case, and to surface seeps in another.

The occurrence of short-circuiting will be difficult to predict, as it will depend on the presence of preferential drainage paths and other unquantifiable inhomogeneities within the waste. However, its main effect will be to limit the effectiveness of the recirculation scheme, whether the intended purpose is flow balancing, accelerating biodegradation or contaminant flushing, rather than any major adverse environmental impact.

7.7 Interaction of leachate and gas

There was widespread reporting of instances where leachate recirculation has led to the filling up of nearby gas wells. These could locally affect gas abstraction efficiency, leading to increased emissions and possible odour risks. One operator had experienced problems with the interaction of leachate and gas flows, mainly in band drains. To counter this, leachate injection is controlled using a typical routine of 1 week recirculation, 1 week standoff and 2 weeks gas extraction. An operator with a specially installed grid of dual-purpose pin wells uses one row (out of five) for gas extraction and the other four for leachate injection, rotating on a weekly basis.

Cox *et al*. (2006) report the abstraction of large amounts of gas from a horizontal leachate well retro-fitted by means of directional drilling near the base of the Rainham landfill. This was an unexpected result, and illustrates that there is much still to be learned about the interaction between gas and leachate flows in waste landfills.

It will be important to maintain required levels of gas extraction and control from any area while practising leachate recirculation, and experience shows this requires careful planning of operations.

8 Monitoring of leachate recirculation

8.1 Issues to be covered by monitoring of leachate recirculation

Preceding sections of the report have highlighted a range of environmental and operational issues that may arise during leachate recirculation. These are summarised in Table 8.1.

Table 8.1 Leachate recirculation issues with implications for monitoring.

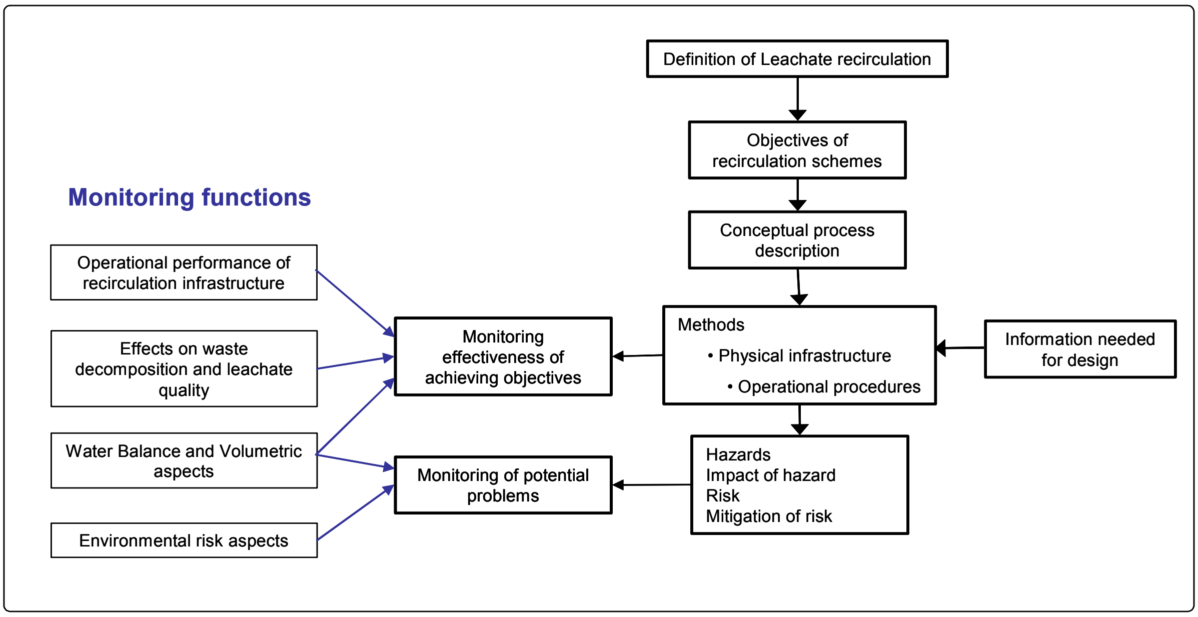
Environmental issues
Odours and uncontrolled gas release
Adverse impact on leachate quality
Uncontrolled build up of head on liner systems
Perching/surface outbreaks
Surface water contamination
Short-circuiting
Interaction of leachate and gas
Clogging of basal drainage layer
Slope instability
Operational issues
Poor performance/clogging of injection infrastructure
Effects of settlement
Clogging of basal drainage layer
Obtaining sufficient volumes to recirculate
Slope instability
Interaction of leachate and gas
Short-circuiting

The range of monitoring to address these issues may be separated into four functional groups, namely:

- operational performance of recirculation infrastructure;
- effects on waste decomposition and leachate quality;
- water balance and volumetric aspects;
- environmental risk aspects.

These are shown in Figure 8.1 in relation to the conceptual framework for evaluation of recirculation schemes.

Figure 8.1 Monitoring issues in relation to the conceptual framework for evaluation of leachate recirculation.



Possible monitoring under each of these headings is presented below. Some of these monitoring activities may already be required by existing Environmental Permits at landfills. However, it would not be appropriate or helpful for all of the listed monitoring to be done on all recirculation projects, as this would not contribute to the protection of the environment. Rather, the lists set out the areas that may need monitoring, and the reasons why certain types of monitoring may be needed. This allows the operator and regulator to develop a monitoring regime that is proportionate.

8.2 Operational performance of recirculation infrastructure

Parameter	Comment
Hydraulic infiltration rate	m^3/m^2/year for areal systems; m^3/linear metre/year for linear systems (e.g. trenches)
Soakaway rate	Rate of head decline in reinjection structures when flow is stopped
Standing head within reinjection structures	Dipmeter through access pipe, or piezometer installed during construction
Visual/CCTV inspection of injection media and access pipes	Looking for accumulation of solids
Clogging potential of recirculated leachate	e.g. SS, VSS, Ca, alkalinity etc Possibly measure before and after pre-treatment such as aeration and filtration
Clogging/loss of performance of basal drainage layers	Not clear how to achieve this, but CCTV surveys may be of some help

Trends/changes

Maintain time series graphs of m^3/m^2/year or m^3/linear metre/year; soakaway rates.

Expect gradual loss of hydraulic performance.

Examine results for evidence of increased head within structure, for a given flow rate – evidence of clogging.

8.3 Effects on waste decomposition and leachate quality

Parameter	Comment
Gas temperature at well heads	Indicate local changes in reaction rates
Gas temperature at manifolds	Indicate overall changes in reaction rates
Leachate temperature in monitoring wells	
Leachate temperature at abstraction points	
Gas flow rates at well heads	
Gas flow rate from recirculation cell	
Settlement rate	Settlement gauges and/or site survey
Gas quality	CH_4, CO_2, H_2 etc
Leachate quality in monitoring points near recirculation zone	Look for flush of acetogenic leachate, or increased NH_4-N

Trends/changes

Gas and leachate temperature changes (e.g. rise) might indicate increased biological activity.

Gas generation rates (e.g. m^3/t/year) in recirculation zone before and after recirculation.

Settlement rate may indicate changes in decomposition rate.

Change in leachate quality (e.g. higher NH_4-N or BOD and COD) may indicate increased activity, or simply flushing from unsaturated zone.

8.4 Water balance and volumetric aspects

Parameter	Comment
Flow from individual landfill cells	
Volumes recirculated	Record location of reintroduction
Flow to Leachate Treatment Plant or to discharge off site	
Imported water or sludge	
Rainfall	Can use nearby Met Office or amateur station data
Evapotranspiration	Use Met Office or estimated daily values
Leachate level	

Maintain time series graphs of:

- leachate level and head within cells; calculated seasonal fluctuation in quantity of stored leachate; (important to know geometry of cell base, to convert head changes to volume changes; also important to state assumptions regarding saturated storage coefficients);
- flow from cells (daily and cumulative in year);
- recirculated flow (daily and cumulative in year);
- flow to Leachate Treatment Plant or discharge (daily and cumulative in year);
- estimated effective rainfall.

Trends/changes

Expect to see seasonal fluctuation in cumulative surplus, and should relate to the volumes being recirculated.

Challenge: how to estimate how much is 'in transit', how much gets absorbed, and what head increase might result if recirculation were stopped at any time.

8.5 Environmental risk aspects

Parameter	Comment
Visual inspection for surface breakouts	Look for surface breakouts, overtopping of cell bunds etc
Visual inspection of transfer pipelines	Look for evidence of leaks that might affect surface water quality, especially where lines cross restored surfaces
Visual inspection of pipelines around injection zones	Differential settlement around injection zones may lead to leaks in gas and leachate pipelines
Pressure changes in gas pipelines	May indicate blockage by leachate from recirculation
CH_4 concentration at site boundary	Set threshold as in some Environmental Permits
Odour, H_2S at site boundary	Set H_2S threshold
Differential settlement around injection zones	
Slope instability	

Trends/changes

Liquid blockages in gas wells and gas pipelines – may show up as sudden pressure changes, possibly amenable to automatic instrumental detection.

Visual inspection for surface breakouts (e.g. from sub-cap trenches).

Visual inspection of transfer pipelines (risk of leakage on to restored surfaces, and surface water contamination).

9 Summary and conclusions

There are numerous possible reasons for carrying out leachate recirculation, and all are being practised to varying degrees except for, apparently, contaminant flushing. Recirculation is an essential part of leachate management for most UK biodegradable waste landfills, both for the buffering of winter flow peaks and for the buffering of COD peaks from new cells. It is also highly beneficial to waste degradation processes and may become necessary for contaminant flushing. It is critical that the objectives of leachate recirculation are clearly articulated so that the appropriate methodology can be selected and suitable monitoring installed. Some of the objectives of recirculation may also be applicable to other types of landfill. Table 9.1 provides a checklist that may help in selection of a suitable method for a particular need.

Table 9.1 General checklist for evaluation of recirculation schemes.

Objectives of scheme	
Are the objectives of the proposed scheme clear?	
Are there multiple objectives or a single objective?	
Conceptual process description	
Has a conceptual process description been prepared?	
Is the conceptual process description adequate for the stated objective?	
Physical infrastructure	
Adequate description of proposed infrastructure?	
Does the proposed infrastructure match the objectives and conceptual process design?	
Operational procedures	
Adequate description of proposed operational procedures?	
Environmental risks	
Has a risk register been prepared?	
Have the potential risks been adequately identified and addressed?	
Minimum scope of risk register:	*Odours and uncontrolled gas release during construction*
	Odours and uncontrolled gas release during operation
	Control of head on liner
	Perching/surface outbreaks from waste body
	Leaks from transfer pipelines
	Identify and rate surface waters at risk of contamination
	Risk of leachate flooding gas lines and impeding gas collection
	Slope stability risks
Monitoring	
Has a scheme for monitoring environmental risks been prepared?	
Is the scheme adequate for the scope of the proposed recirculation?	

Surveyed UK operators show a high level of enthusiasm for recirculation, with seasonal flow balancing and stimulation of degradation being the most commonly given reasons for doing it. The quantities being recirculated are typically in the range 5000 to 20,000 m^3/year. This is probably not sufficient to have a significant effect on gas generation. It is not certain that recirculation alone could ever be enough to stimulate faster rates of degradation in drier parts of the UK, without the introduction of external water sources.

A wide range of infrastructure designs has been used and there has been some evolution to more effective systems. While there has been relatively little quantitative monitoring of either the engineering or environmental performance of recirculation systems to date, some useful observations on performance have emerged, e.g.

- The review has assessed the range of application rates (both infrastructure rates and areal rates) for different types of injection system. These are summarised in Table 6.1.
- The lateral zone of influence of most systems appears to be limited to 5 to 15 m.

It is clear that some designs could accommodate very large volumes, but it is not yet known how long this could be sustained. The main operational problem areas appear to be:

- **Clogging of injection infrastructure** over a period of just a few weeks appears common when the injected leachate is acetogenic. It would appear still to be a significant challenge to accommodate recirculation during the acetogenic period using subsurface systems.
- Localised **flooding** of gas wells is clearly a common risk during recirculation. An alternating mode of operation appears to be the best approach to overcome these problems and is used routinely by several operators interviewed during this study, as well as being referred to in literature.

The main environmental issues appear to be:

- **Surface breakouts**. These may occur due to lateral movement along layers of daily cover, or as a consequence of high pressures caused either by pressure injection or by sub-cap systems being constructed to a fall instead of horizontal.
- **Odours, gas release and the potential for air ingress** were identified as significant issues during the installation of band drains, due to the rapid placement of densely spaced bores and may also apply to other types of injection system, especially if they are not adequately capped.

There are many other perceived problems, such as uncontrolled build up of leachate head, and clogging of basal drainage layers, for which there appears little evidence.

There appears to be some evidence that high pressure leachate injection can exacerbate surface breakouts and the flooding of other infrastructure. By increasing pore-pressure it could also increase the risk of slope failure.

Greater attention must be paid to the conceptual design to meet the objectives of recirculation and to monitoring the operation. The review has developed an overall evaluation framework, a checklist for evaluating schemes and initial suggestions for the monitoring that may be appropriate. It must be emphasised that these should be applied in a way that is proportionate and necessary for individual proposals.

Finally, it is recommended that details of recirculation schemes be incorporated into site leachate management plans.

References

Al-Thani, A.A., Beaven, R.P. and White, J.K., 2004. Modelling flow to leachate wells in landfills. *Waste Management*, 24 (3), 271–276.

Augenstein, D., Yazdani, R., Kieffer, J. and Benemann, J., 2005a. Yolo County, California Controlled Landfill Program: a summary of results since 1994. *Proceedings Sardinia 2005, Tenth International Waste Management & Landfill Symposium. S*. Margherita di Pula, Cagliari, Italy.

Augenstein, D., Yazdani, R., Kieffer, J., Sananikone, K. and Benemann, J., 2005b. Yolo County Controlled Landfill Project status after 12 years of operation. *Proceedings of 29th Annual SWANA Landfill Gas Symposium, St Petersburg, Florida*, 27–30 March.

Barber, C. and Maris, P.J., 1984. Recirculation of leachate as a landfill management option: benefits and operational problems*. Quarterly Journal of Engineering Geology London*, 17, 19–29.

Barina, G., 2005. Effect of leachate recirculation on the stabilisation of organic matter in municipal solid waste. *Proceedings of International Workshop Hydro-Physico-Mechanics (HPM) of Landfills*. LIRIGM, Grenoble, 21–21 March.

Barina, G., Budka, A., Gisbert, T., Guyonnet, D., Puglierin, L. and Cirino, N., 2001. Identification and assessment of leachate recirculation effects at real-scale landfill. In: Christensen, T.H., Cossu, R. and Stegmann, R. (eds), *Eighth International Waste Management and Landfill Symposium, Proceedings Sardinia 2001*. S. Margherita di Pula, Cagliari, Italy, CISA, vol. II, pp. 95–104.

Barina, G., Gisbert, T., Puglierin, L., Boin, B., Lefebvre, X. and Gemignani, A., 2003. Integrated study of waste characteristics, effluents and waste mass evolution after 4 years of large scale recirculation. In: Christensen, T.H., Cossu, R. and Stegmann R. (eds), *Ninth International Waste Management Symposium, Sardinia 2003*. Cagliari, Italy.

Barina, G., Oberti, O. and Budka, A., 2005. Leachate recirculation by horizontal trenches: a new French experience. In: Cossu, R. and Stegmann, R. (eds), *Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium*. S. Margherita di Pula, Cagliari, Italy, 3–7 October 2005. CISA, Italy.

Benson, C.H., Barlaz, M.A., Lane, D.T. and Rawe, J.M., 2007. Practice review of five bioreactor/recirculation landfills. *Waste Management, 27 (1), 13-29.*

Blakey, N.C. and Maris, P.J., 1987. On-site leachate management – anaerobic processes. *Proceedings, First Sardinia International Landfill Symposium*. Santa Margherita di Pula, Cagliari, Italy, 19–23 October 1987. Vol. I, paper XXI, 15 pp.

Blakey, N.C., Bradshaw, K., Reynolds, P. and Knox, K., 1997. Bio-reactor landfill – a field trial of accelerated waste stabilisation*. Proceedings Sardinia 97, Fifth International Landfill Symposium*. S. Margherita di Pula, Cagliari, Italy, 13–19 October 1997. Vol. I, pp. 375–385.

Bureau, N., Aran, C. and Hebe, I., 2005. Bioreactor monitoring: assessment of performances. In: Rathje, E.M. (ed.), *Proceedings Geo-Frontiers 2005,* Austin, Texas, 24–26 January – Geotechnical Special Publications Nos. 130–142. ASCE, Austin, Texas.

Burton, S.A.Q., Beaven, R.P. and White, J.K., 2004. The effect of moisture content in controlling landfill gas production and its application to a model for landfill refuse decomposition. *Proceedings Waste 2004 Conference, Stratford on Avon, 28–30 September 2004*, pp. 333–342.

Cox, S.E., Beaven, R.P., Powrie, W. and Cole, D.J., 2006. Installation of horizontal wells in landfilled waste using directional drilling. *Journal of Geotechnical and Geoenvironmental Engineering* 132 (7), 869-878.

Environment Agency, 2004. *Guidance on the Management of Landfill Gas*. Landfill Directive Report LFTGN03. Environment Agency, Bristol, UK.

Environment Agency, 2009. *Sector Guidance Note for Landfill.* EPR 5.02. Environment Agency, Bristol, UK.

Guerin, R., Munoz, M.L., Aran, C., Laperrelle, C., Hidra, M., Drouart, E. and Grellier, S., 2004. Leachate recirculation: moisture content assessment by means of a geophysical technique. *Waste Management*, 24 (8), 785–794.

Haydar, M.M. and Khire, M.V., 2005. Leachate recirculation using horizontal trenches in bioreactor landfills. *Journal of Geotechnical and Geoenvironmental Engineering*, 131 (7), 837–847.

Haydar, M.M. and Khire, M.V., 2007. Leachate recirculation using permeable blankets in engineered landfills. *Journal of Geotechnical and Geoenvironmental Engineering,* 133 (4), 360–371.

Holmes, R., 1980. The water balance method of estimating leachate production from landfill sites. *Solid Wastes,* January, 20–30.

Hudson, A., Beaven, R.P. and Powrie, W., 2001. Interaction of water and gas in saturated household waste in a large scale compression cell. In: Christensen, T.H., Cossu, R. and Stegmann, R. (eds), *International waste management and landfill symposium. Sardinia 2001*. Cagliari, Italy. CISA, pp. 585–594.

ITRC, 2006. Characterization, design, construction and monitoring of bioreactor landfills. *ALT-3 Washington DC*. Interstate Technology & Regulatory Council, Alternative Landfill Technologies Team http://www.itcrweb.org/

Jain, P., Powell, J., Townsend, T.G. and Reinhart, D.R., 2006. Estimating the hydraulic conductivity of landfilled municipal solid waste using the borehole permeameter test. *Journal of Environmental Engineering-ASCE,* 132 (6), 645–652.

Kasali, G.B. and Senior, E., 1989. Effects of temperature and moisture on the anaerobic-digestion of refuse. *Journal of Chemical Technology and Biotechnology,* 44 (1), 31–41.

Khire, M.V. and Haydar, M.M., 2003. Numerical evaluation of granular blankets for leachate recirculation in MSW landfills. In: Christensen, T.H., Cossu, R. and Stegmann, R. (eds), *Ninth International Waste Management Symposium, Sardinia 2003*, Cagliari, Italy.

Khire, M.V. and Haydar, M.M., 2007. Leachate recirculation in bioreactor landfills using geocomposite drainage material. *Journal of Geotechnical and Geoenvironmental Engineering*, 133 (2), 166–174.

Khire, M.V. and Mukherjee, M., 2007. Leachate injection using vertical wells in bioreactor landfills. *Waste Management,* 27 (9), 1233–1247.

Klink, R.E. and Ham, R.K., 1982. Effects of moisture movement on methane production in solid waste landfill samples. *Resources and Conservation*, 8, 29–41.

Knox, K., 1990. The relationship between leachate and gas. *Proceedings, International Conference Landfill Gas: Energy and Environment Conference*, ETSU/DOE, Bournemouth, UK (16–19 October). ISBN 0-7058 1628-1, pp. 367–386.

Knox, K. and Shaw, P.J., 2006a. A study of the hydraulic response of landfills to infiltration events. *Waste 2006, Sustainable Waste and Resource Management*, Stratford upon Avon, The Waste Conference Limited, pp. 411–420.

Knox, K. and Shaw, P.J., 2006b. An experimental study of the hydraulic response of landfills to infiltration events. *Final Report to the Norlands Foundation*. Entrust Project no. 222285.003.

McCreanor, P.T., 1998. *Landfill Leachate Recirculation Systems: Mathematical Modeling and Validation*. PhD Dissertation, University of Central Florida, Orlando.

McCreanor, P.T. and Reinhart, D.R., 1996. Hydrodynamic modeling of leachate recirculating landfills. *Water Science and Technology*, 34 (7–8), 463–470.

McCreanor, P.T. and Reinhart, D.R., 1999. Hydrodynamic modeling of leachate recirculating landfills. *Waste Management & Research*, 17 (6), 465–469.

McCreanor, P.T. and Reinhart, D.R., 2000. Mathematical modeling of leachate routing in a leachate recirculating landfill. *Water Research*, 34 (4), 1285–1295.

Mehta, R., Barlaz, M.A., Yazdani, R., Augenstein, D., Bryars, M. and Sinderson, L., 2002. Refuse decomposition in the presence and absence of leachate recirculation. *Journal of Environmental Engineering-ASCE*, 128 (3), 228–236.

Moreau, S., Bouyé, J.M., Barina, G. and Oberti, O., 2003. Electrical resistivity survey to investigate the influence of leachate recirculation in a MSW landfill. In: Christensen, T.H., Cossu, R. and Stegmann, R. (eds), *Ninth International Waste Management Symposium*, *Sardinia 2003*. Cagliari, Italy.

Moreau, S., Bouyé, J.M., Duquennoi, C., Barina, G. and Oberti O., 2004. Electrical resistivity survey to investigate biogas migration under leachate recirculation events. In: *Proceedings Waste 2004 Conference, Stratford-upon-Avon, 28–30 September,* pp 663-672*.* The Waste Conference Ltd.

Moreau-Le-Golvan, Y., Lagier, T., Smith, L. and Lane, M., 2005. A strategy to achieve optimal performance at full-scale operational bioreactor landfill. In: Cossu, R. and Stegmann, R. (eds), *Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium*. S. Margherita di Pula, Cagliari, Italy, 3–7 October 2005. CISA, Italy.

Morris, J.W.F., Vasuki, N.C., Baker, J.A. and Pendleton, C.H., 2003. Findings from long-term monitoring studies at MSW landfill facilities with leachate recirculation. *Waste Management*, 23 (7), 653–666.

Mouchel Consulting Ltd, 2001. *The Brogborough Test Cells: Final Report, Gas Monitoring and Hydraulics of Leachate Recirculation*. Environment Agency, R&D Technical Report: HOCO-231/1. Contract no: P1-352. 122 pp.

Palmer, C., 1982. Leachate control – site engineering aspects. *Proceedings of Landfill Leachate Symposium*. AEA Technology, Harwell, 19 May, 7 pp.

Pohland, F.G., 1975. *Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment*. US Environmental Protection Agency, Cincinnati, Ohio, EPA-600/2-75-043.

Powrie, W. and Beaven, R.P., 1999. Hydraulic properties of household waste and implications for landfills. *Proceedings Institution Civil Engineers Geotechnical Engineering*, 137 (4), 235–247.

Rees, J.F. and Grainger, J.M., 1982. Rubbish dump or fermenter – prospects for the control of refuse fermentation to methane in landfills. *Process Biochemistry*, 17 (6), 41–44.

Reinhart, D.R., 1996. Full-scale experiences with leachate recirculating landfills: case studies. *Waste Management & Research*, 14 (4), 347–365.

Robinson, H.D., Barber, C. and Maris P.J., 1982 Generation and treatment of leachate from domestic wastes in landfills. *Water Pollution Control,* 81 (4), 465-478.

Skhiri, N., Guerbois, M. and Hebe, I., 2006. Technical and environmental performances assessment for a bioreactor. In: Lagerkvist, A. (ed.), *ICLRS 06 – Abstract Proceedings of the 4th Intercontinental Landfill Research Symposium*. Gallivare, Sweden, pp. 183–184.

Thiel, R., 2005. Observed benefits and problems associated with leachate recirculation. *Proceedings Sardinia 2005*. S. Margherita di Pula, Cagliari, Italy, 3–7 October 2005, CD only.

Townsend, T.G. and Miller, W.L., 1998. Leachate recycle using horizontal injection. *Advances in Environmental Research*, 2 (2), 129–138.

Townsend, T.G., Miller, W.L. and Earle, J.F.K., 1995. Leachate recycle infiltration ponds. *Journal of Environmental Engineering*, 121 6), 465–471.

USEPA, 1995. EPA/600/R-95/146 seminar publication: *Landfill Bioreactor Design and Operation*. 23–24 March 1995, Wilmington, Delaware.

USEPA, 2004. *Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills*, 22 March 2004, 40 CFR Part 258.

Vasuki, N., 1993. Practical experiences with landfill leachate recirculation in pilot and field scale units. *31st Annual International Solid Waste Exposition*, SWANA.

Woelders, H., Luning, L., Van Velthoven, F., Hermkes, H. and Oonk, H., 2005. Dutch Sustainable Landfill Research program: four years experience with the bioreactor test cell Landgraaf. In: Cossu, R. and Stegmann, R. (eds), *Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium*. S. Margherita di Pula, Cagliari, Italy, 3–7 October 2005. CISA, Italy.

Yazdani, R., Kieffer, J., Sananikone, K. and Augenstein, D., 2006. Full scale bioreactor landfill for carbon sequestration and greenhouse emission control. Final Technical Progress Report. *Yolo County, Planning and Public Works Department*. D.O.E. Award Number DE-FC26-01NT41152 http://www.yolocounty.org/recycle/bioreactor.htm

Appendix. Leachate recirculation in a landfill: a simple 1-D model

Background and objectives

Leachate is the liquid phase present in the pore spaces of the solid waste material in a landfill. The leachate arises from the liquid content of the waste when it is placed in the landfill, and from rainfall infiltration of water through the upper surface of the landfill. Leachate may be collected from the waste using wells or drains. It can then either be treated and disposed of, or reintroduced into the waste material through an artificial recharge system. This latter process is known as leachate recirculation; managing the leachate in this way may be used to optimise both gas generation and leachate treatment systems.

In this note, a simple numerical model of the concept of landfill leachate recirculation is developed and used to gain some insight into the basic mechanics of the process by identifying the underlying relationships between the key parameters involved. The analytical approach used in the model is then validated with reference to real data from the landfill at Beddington, Croydon, South London.

Water content

For the purposes of this note, the ratio of the volume of leachate in an element of waste to the volume of that element will be termed the *water content* of the waste. The free surface of the leachate-saturated zone in the waste, along which the pore-pressure is zero relative to atmospheric pressure, will be termed the *water table*.

At any point in time the water content will vary throughout the waste material. As the material in a lined site becomes saturated, hydrostatic pore-pressures will build up on the base of the landfill and the risk of basal leakage will increase. To prevent this, a basal drainage blanket is often installed from which leachate may be extracted, lowering the water table and reducing the pressures on the liner. Above the water table, pore-pressures will be negative as the result of surface tension effects resisting the vertical drainage of leachate towards the water table. Within this zone of negative pore-pressures the water content is generally reduced below saturation levels. Conventional models of seepage in partly saturated soils often invoke a one to one relationship between pore-pressure and water content of the form indicated in Figure A1.1. In reality, different curves are followed during wetting and drying, and both will vary depending on the void ratio.

Figure A1.2 illustrates a situation in which drainage has reduced the leachate water table to just above the basal drainage layer. At this level the pore-pressure will be zero relative to atmospheric pressure. Above this level the value of pore-pressure will become increasingly negative with elevation. The water content will also fall with elevation following a relationship such as that shown in Figure A1.1, and as illustrated in Figure A1.2.

If leachate or fresh liquid is introduced through a surface injection layer, as shown in Figure A1.3, the water content builds up below the injection layer, and the distribution of water content changes from curve A in Figures A1.2 and A1.3, to a transient distribution illustrated by curve B in Figure A1.3.

The rate of infiltration will sustain a new level of partial saturation at the upper boundary of the waste material. If the rate of infiltration is high enough the material will become fully saturated and the pore-pressure at the upper boundary will be zero. Infiltration rates higher than this will result in ponding and the pore-pressures at the upper boundary rising above zero.

The new level of saturation will progress downwards from the injection layer through the waste material until it reaches the level above the lower boundary at which the water content is the same as that of the new saturation level. There will be a corresponding relief of negative pore-pressure in the upper zone of the material.

The effect is to store a quantity of leachate in the waste material. At any point in time, the amount stored is the difference between the water contents represented by the distribution curves B and A.

This potential for storing leachate offers a way in which the seasonal variations in leachate flows to a landfill leachate treatment plant can be smoothed out to optimise the performance of the plant. Similarly the potential for changing the water content, upon which gas generation depends, offers a way of optimising the gas generation from the waste.

Storage rates

The rate at which storage can be achieved, and the water content changed, depends on the values of the physical parameters that determine the behaviour of seepage flow in the waste material. A simple conceptual model of the mechanism of saturation can be represented analytically and may be used to assess the order of magnitude of the rate of storage as follows.

The two main parameters are the hydraulic conductivity k and the area of flow A. These are conventionally related to seepage flow q through Darcy's law,

$$q = Aki \quad (1)$$

where i is the hydraulic gradient driving the flow q.

In partly saturated conditions the area of flow A reduces as the result of the reduction of water content. Conventionally this effect is modelled by keeping the area constant and reducing the value of the hydraulic conductivity k instead. A typical relationship between hydraulic conductivity and negative pore-pressure, which is assumed for the purposes of modelling seepage flows in partly saturated conditions, $k(p)$, is shown in Figure A1.4. The relationship between hydraulic conductivity and water content implied by Figures A1.1 and A1.4, $k(\theta)$, is shown in Figure A1.5.

In equation (1) i, the hydraulic gradient, is the total head gradient driving the flow expressed in terms of the head of the seepage fluid, in this case leachate. In the partly saturated zone in the situation illustrated in Figure A1.2, the pressure just above the water table will be zero, and the initial pressure just below the injection layer will be that corresponding to the new level of saturation θ_I. The pore-pressure will be $p(\theta_I)$, which will be a negative quantity if $\theta_I < \theta_S$ where θ_S is the saturated water content, see Figure A1.1.

As the upper zone in which the water content is θ_I grows, the pore-pressures $p(\theta_I)$ will be established throughout the zone. The overall pressure gradient driving the flow into the upper zone will thus be due to the depth of the upper zone, Δz, times the average specific weight of the liquid/gas fluid, γ, that exists in the upper zone, $\gamma\ \Delta z$ kPa. In terms of head of leachate this is $\gamma \Delta z / \gamma_W$ metres of water. The head gradient is this divided by Δz, that is γ / γ_W. An approximation to this is

$$\frac{\gamma}{\gamma_W} = \frac{\theta_I - \theta_D}{\theta_S - \theta_D} \quad (2)$$

where θ_S is the saturated water content, and θ_D is the average drained water content.

This assumes that the liquid associated with the drained water content θ_D is not mobile, so that the mass of free water per unit total volume is given by $m_w = (\theta_I - \theta_D) \times \rho_w$ and the volume of drainable voids per unit total volume is $(\theta_S - \theta_D)$, giving $\rho/\rho_w = \gamma/\gamma_w = (\theta_I - \theta_D)/(\theta_S - \theta_D)$.

Thus following equation (1) the recharge flow q_R replenishing the water content deficit $\theta_I - \theta_D$ is of the order of,

$$q_R = Ak(\theta_I)\frac{\theta_I - \theta_D}{\theta_S - \theta_D} \quad (3)$$

The volume of the deficit is approximately $(\theta_I - \theta_D)A\Delta z$, where Δz is the depth of the waste material. At a rate q_R, this will fill in a time of,

$$\frac{(\theta_I - \theta_D)A\Delta z}{q_R} = \frac{\Delta z(\theta_S - \theta_D)}{k(\theta_I)} \quad (4)$$

If D is the overall depth of the waste material the time to fill the overall depth will be

$$\frac{D(\theta_S - \theta_D)}{k(\theta_I)}.$$

The above analysis assumes that the functional relationships involved are independent of depth. In fact this is almost certainly not the case. There is for example a known variation of both saturated hydraulic conductivity and drainable porosity with depth. The sensitivity of the estimates based on the current analysis to the depth related issues is outside the scope of the present study.

Comparison with a more rigorous numerical analysis

The analysis described in the previous section is approximate. In this section, to assess its potential applicability, its results are compared with two examples of vertical leachate infiltration into an initially partly saturated landfill (termed Case A and Case B), analysed numerically but more rigorously using the two-dimensional finite element package, SEEP/W.

A typical finite element grid and boundary nodes are shown in Figure A1.6. In the first example, Case A, the relationships given in Figures A1.1 and A1.4 have been used with an initial pore-pressure distribution in the zone above the water table limited to -10 kPa. Figure A1.1 shows that this corresponds to a water content of 0.25 (compared with a fully saturated value of 0.35). The pore-pressures at the upper and lower boundary nodes were set at zero. The distribution of water content with time, calculated by the model, is given in Figure A1.7, where it can be seen that a waste depth of about 15 m fully saturates over a period of 4 days.

The pressure distribution calculated by the model is given in Figure A1.8, where again it can be seen that the pore-pressures generally recover to zero everywhere.

From Figure A1.4 the saturated hydraulic conductivity is 4.5 x 10^{-6} m/s. $\theta_I - \theta_S$ is therefore 0.1 and Δz is 15m, thus using equation (4) to estimate the storage time,

$\Delta z(\theta_S - \theta_D)/K(\theta_I)$ = 15 x 0.1 x 10^{-6}/(4.5 x 3600 x 24) = 3.9 days which is very close to the time calculated by SEEP/W.

The analysis was repeated (Case B), but the initial negative pore-pressures were limited to -50 kN/m^2 reducing the initial water content to 0.193. The result in Figure A1.9 shows that a depth of 17 m saturates in a period of 7 days. The corresponding pore-pressure distributions are shown in Figure A1.10.

Thus, $\Delta z(\theta_s - \theta_D)/k(\theta)$ = 17 x 0.157 x 10^{-6}/(4.5 x 3600 x 24) = 6.9 days which again corresponds well with the SEEP/W calculation.

Application of the approximate analytical model to data from Beddington Landfill

Beddington Landfill, Croydon, South London, has been the site of a Landfill Tax Credit Scheme funded research project between July 2000 and January 2006 into the hydraulic response of landfills to infiltration events (Knox and Shaw 2006a, 2006b). The 1 ha clay capped test cell contains a gravel drainage layer across the whole base of the site, into which 20 vibrating wire piezometers were installed to monitor leachate heads. Among other findings, the study demonstrated excellent hydraulic continuity across the whole drainage blanket and the rapid response in hydraulic heads to both rainfall infiltration events, and leachate pumping. A 30-m long leachate injection trench was installed in the top of waste below the cap and used to reintroduce leachate pumped out of the drainage system, into the test cell for most of 2005. It is estimated that during late summer 2005, leachate recirculation rates through the system had stabilised at approximately 9 m^3/day and low leachate heads were maintained across the whole basal drainage system.

On 20 September leachate pumping (and recirculation) were halted in a planned exercise to monitor the impact on leachate levels. Over the following 2 months leachate heads rose by 2 m and then stabilised at 2.2 m above the monitored levels during recirculation (Figure A1.11). Leachate recirculation restarted in late December 2005, resulting in a rapid reduction in leachate levels in the drainage blanket. The increase in levels was caused by the draining down of leachate held in transit within the landfill.

An analytical model based on the theory detailed above has been implemented into a spreadsheet and used to analyse the Beddington data in the following way:

- The average depth of the landfill through which leachate recirculation was occurring was 20 m. A 15-layer analytical model was established with each layer representing a 1.33 m waste thickness.
- The leachate injection trench was 30 m long. It is assumed that waste 10 m either side of the trench was influenced by recirculation – i.e. that recirculation occurred through a surface area of 600 m^2, and that 12,000 m^3 of waste was affected.
- Values of θ_S = 50% and θ_D = 45% were selected on the basis of (a) data on volumetric water contents at an applied stress of 100 kPa (mid depth of this site) of an MSW (Figures 6.10, reproduced as Figure A1.12) and an aged waste (Figure 6.12) in Beaven (2000); and (b) a drainable porosity of 1.6%

calculated by Knox and Shaw (2006b) from other pumping tests at the site (this value also corresponds with the graphs in Beaven 2000).

- Ks = 0.023 m/day (2.7 x 10^{-7} m/s). This value is entirely plausible for a 20 m deep landfill, if good waste compaction had been achieved during landfilling.
- A steady state infiltration of 15 mm/day (equivalent to 9 m^3/day over a 600 m^2 area) was applied for the first 180 days. This was to establish steady state recirculation.
- Infiltration was then stopped for the next 100 days (representing the period from 20 September to 29 December 2005).
- The analytical model calculated the amount of leachate draining down through the 20 m depth of waste. The volume produced for a 600 m^2 plan area of draining waste was calculated over time. Drainage had virtually stopped 70 days after recirculation was stopped.
- The volume of leachate draining from the 600 m^2 of affected landfill was assumed to feed into the basal drainage layer and contribute to a rise in leachate levels over the full 1 ha area of the cell.

The modelled rise in leachate level was accurately simulated with a drainable porosity value of 2% (see Figure A1.7). This is similar to the drainable porosity of 1.6% calculated by Knox and Shaw (2006b) from other pumping tests at the site.

Observations

The relevance to waste material of the relationships shown in Figures A1.1 and A1.4, between hydraulic conductivity, water content and pore-pressure needs to be reviewed. In particular, the effects of wetting/drying hysteresis and differences in void ratio need to be considered. It is probable that the hydraulic conductivity levels used in the SEEP/W examples are too high. Lower values would result in a longer time to fill, and a longer residence time.

The SEEP/W model assumes that the initial pore-pressures above the water table fall linearly and negatively with elevation from zero at the water table to a limit of negative pore-pressure set by the user. This limit was set to -10 kN/m^2 and -50 kN/m^2, in Cases A and B respectively. A more refined approach would be to carry out a preliminary run of a drained model to set up this initial pore-pressure distribution.

Outcomes

The outcomes of this study are as follows:

1. Some of the key parameters controlling the response of the waste mass to leachate recirculation have been identified.
2. Approximate relationships between these key parameters have been proposed.
3. Equation (3) offers the potential for developing a relationship between the *recharge flow capacity* of a landfill and its physical characteristics.
4. Equation (4) offers the potential for developing a relationship between the *leachate storage capacity* of a landfill and its physical characteristics.
5. Equation (4) offers the potential for developing a relationship between the *time of leachate retention* in a landfill and its physical characteristics.

References

Beaven, R.P., 2000. *The Hydrogeological and Geotechnical Properties of Household Waste in Relation to Sustainable Landfilling*. PhD Thesis, Department of Civil Engineering. QMW, University of London.

Knox, K. and Shaw, P.J., 2006a. A study of the hydraulic response of landfills to infiltration events. *Waste 2006, Sustainable Waste and Resource Management*, Stratford upon Avon, The Waste Conference Limited, pp. 411–420.

Knox, K. and Shaw. P.J., 2006b. An experimental study of the hydraulic response of landfills to infiltration events. *Final Report to the Norlands Foundation*. Entrust Project no. 222285.003.

Notation

A	cross-sectional area of flow
D	depth of waste
i	hydraulic gradient
k	Darcy hydraulic conductivity
k_s	saturated hydraulic conductivity
p	(negative) pore-pressure
q	volumetric flow rate
q_R	recharge (reinjection) flow rate
z	depth ordinate
Δz	thickness of surface zone
γ	overall unit weight of gas/liquid pore fluid
γ_w	unit weight of water
θ	volumetric water content
θ_D	volumetric water content in drained conditions (at field capacity)
θ_I	volumetric water content in a general condition
θ_S	volumetric water content in saturated conditions

Figures

Figure A1.1 Example of the relationship between water content and pore-pressure.

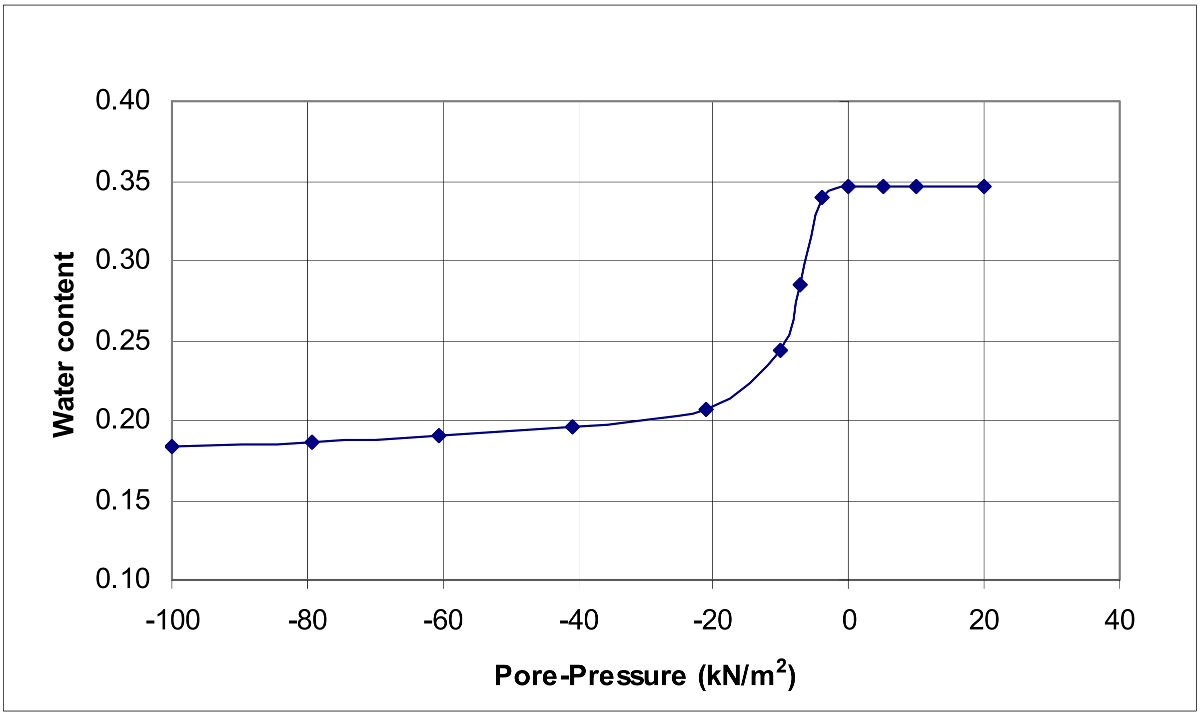


Figure A1.2 Conceptual diagram of initial water content distribution in a fully drained landfill.

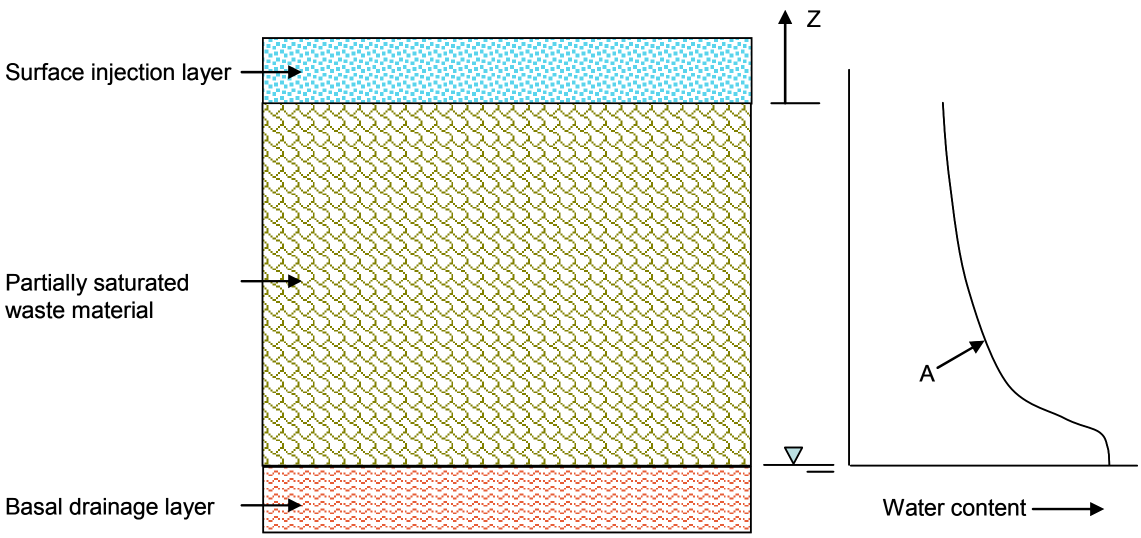


Figure A1.3 Transient water content following start up of recirculation.

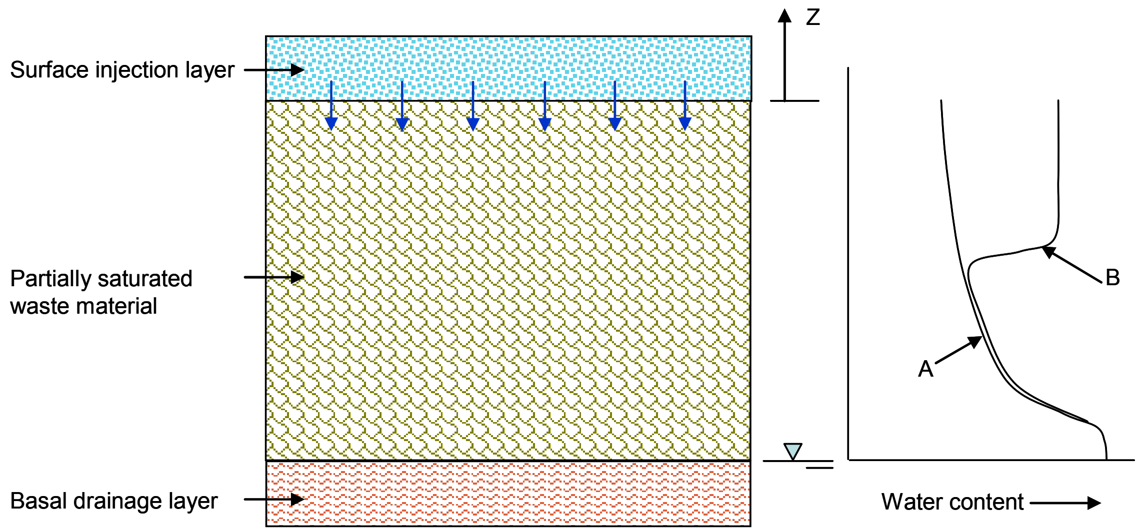


Figure A1.4 Example of the relationship between hydraulic conductivity and pore-pressure.

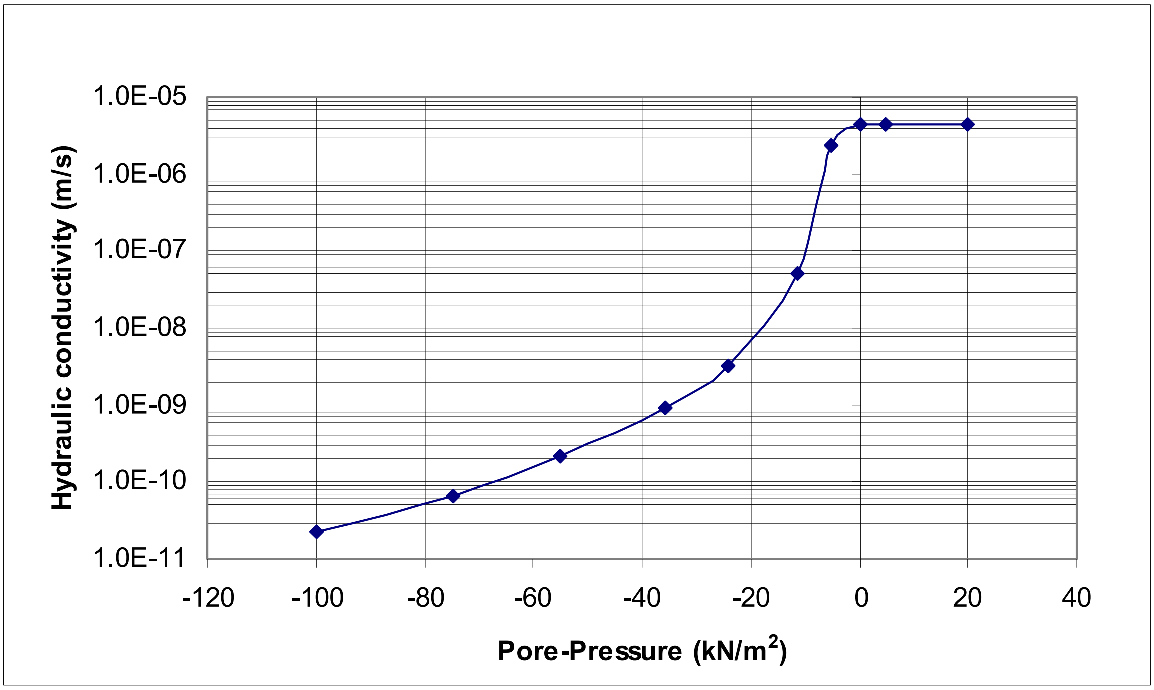


Figure A1.5 The relationship between hydraulic conductivity and water content implied by the relationships shown in Figures A1.1 and A1.4.

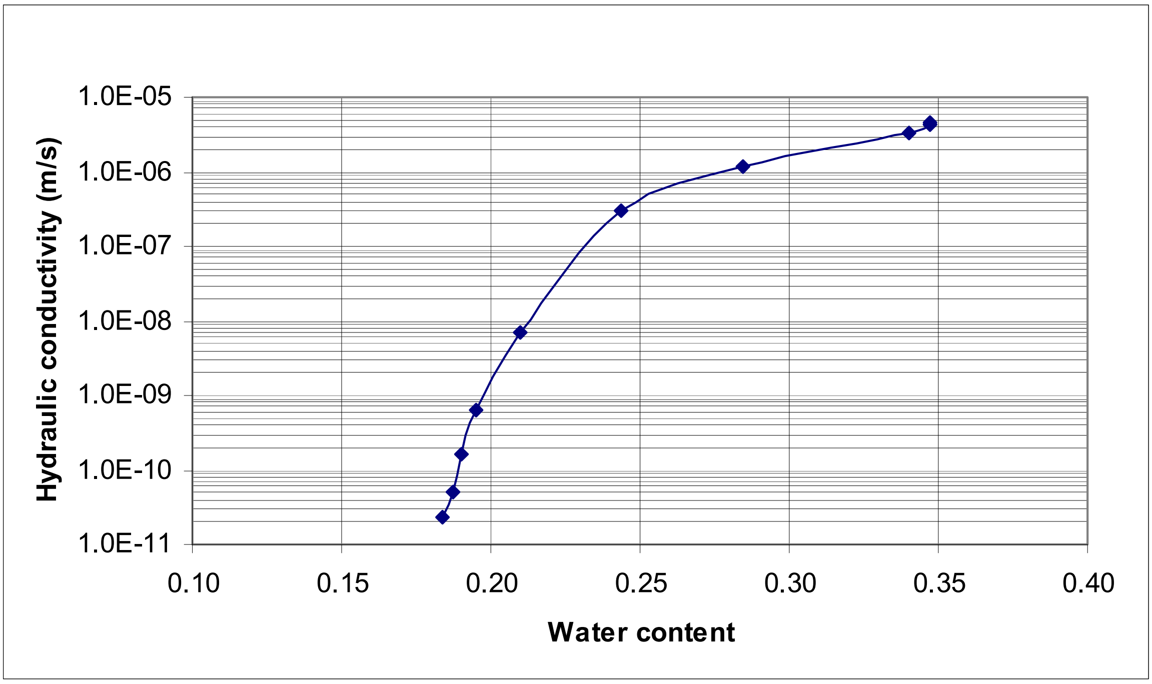


Figure A1.6 Example of SEEP/W model cross-section showing element grid and location of boundary nodes.

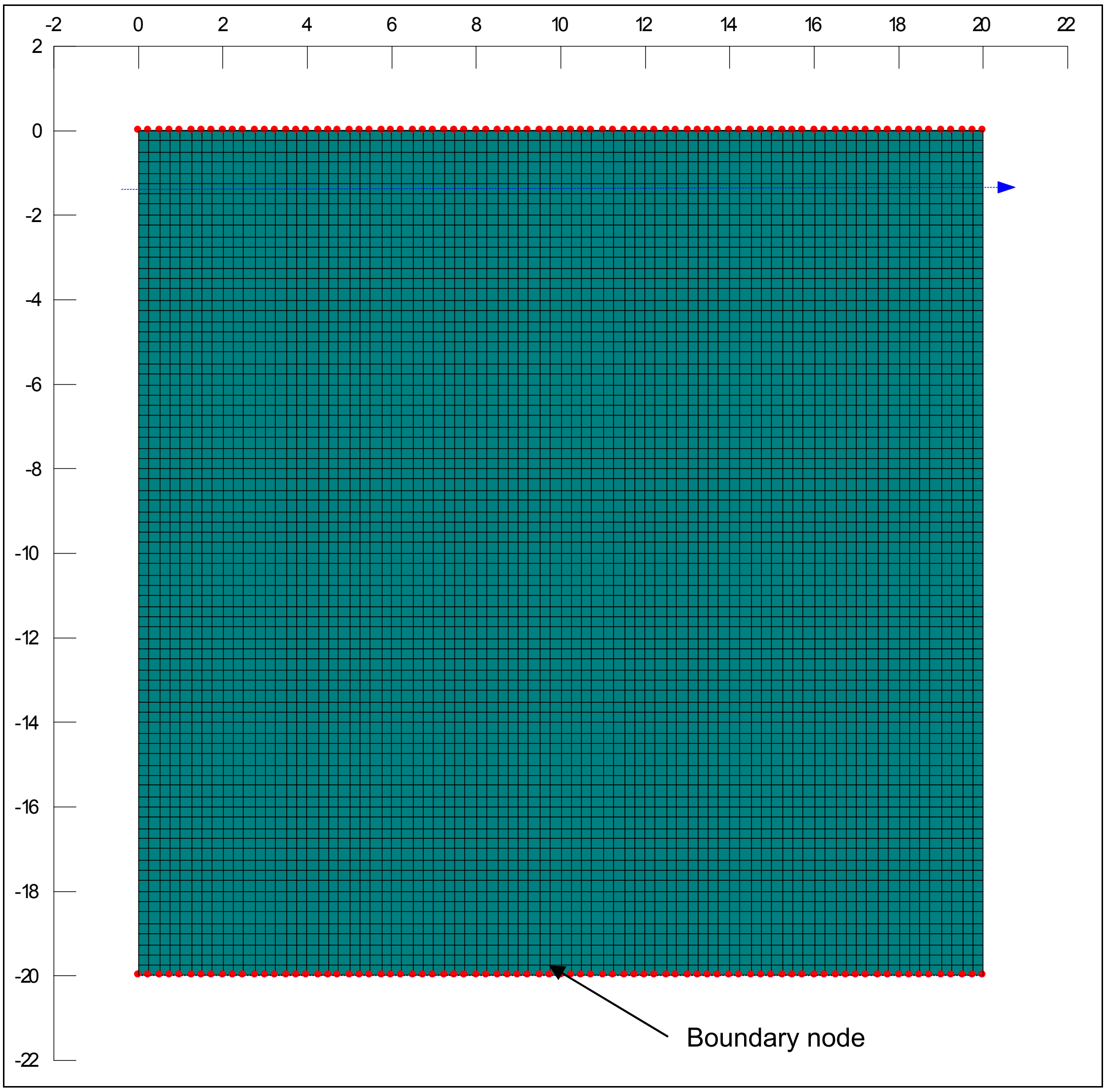


Figure A1.7 SEEP/W result showing transient of water content distribution for Case A.

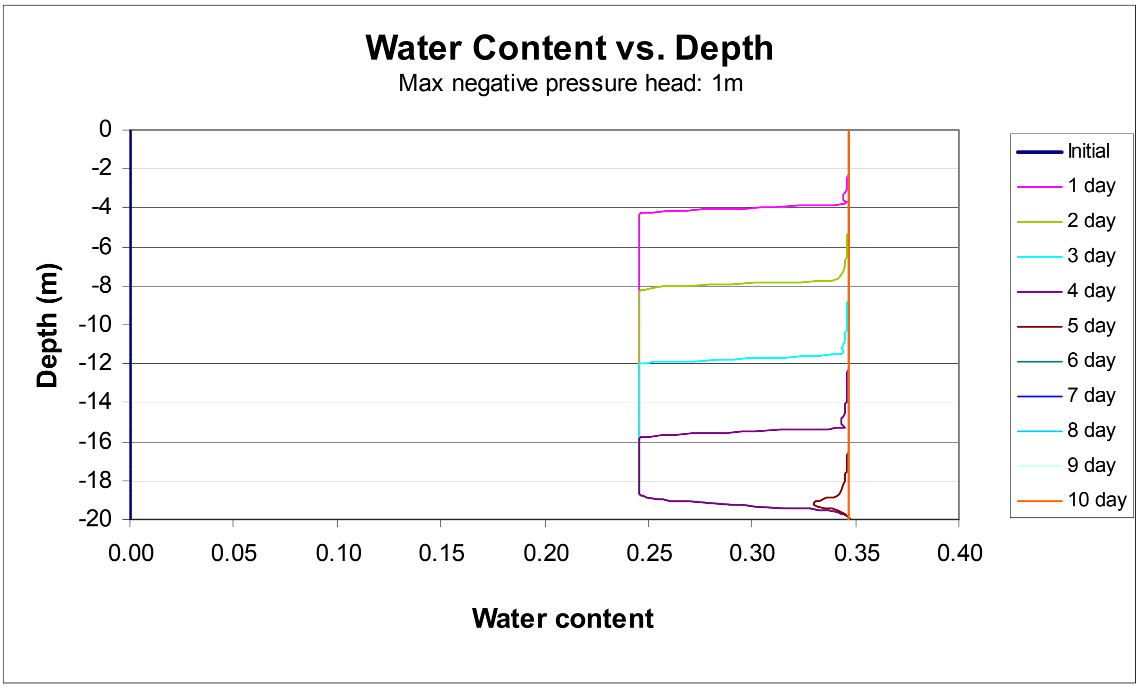


Figure A1.8 SEEP/W result showing transient of pore-pressure distribution for Case A.

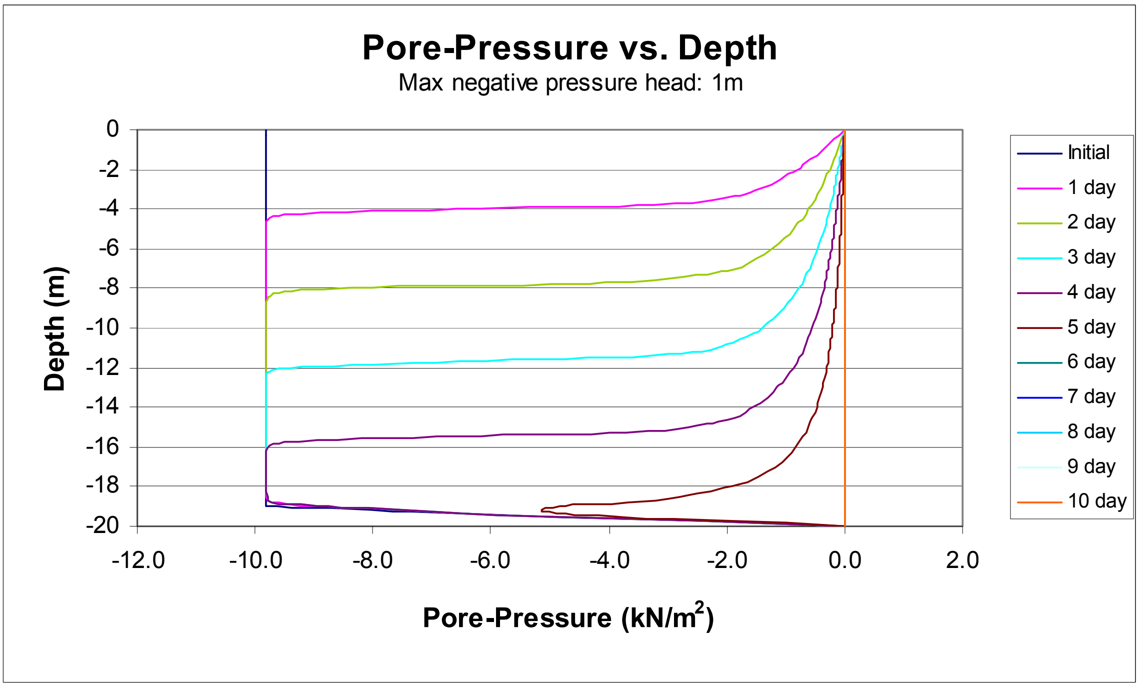


Figure A1.9 SEEP/W result showing transient of water content distribution for Case B.

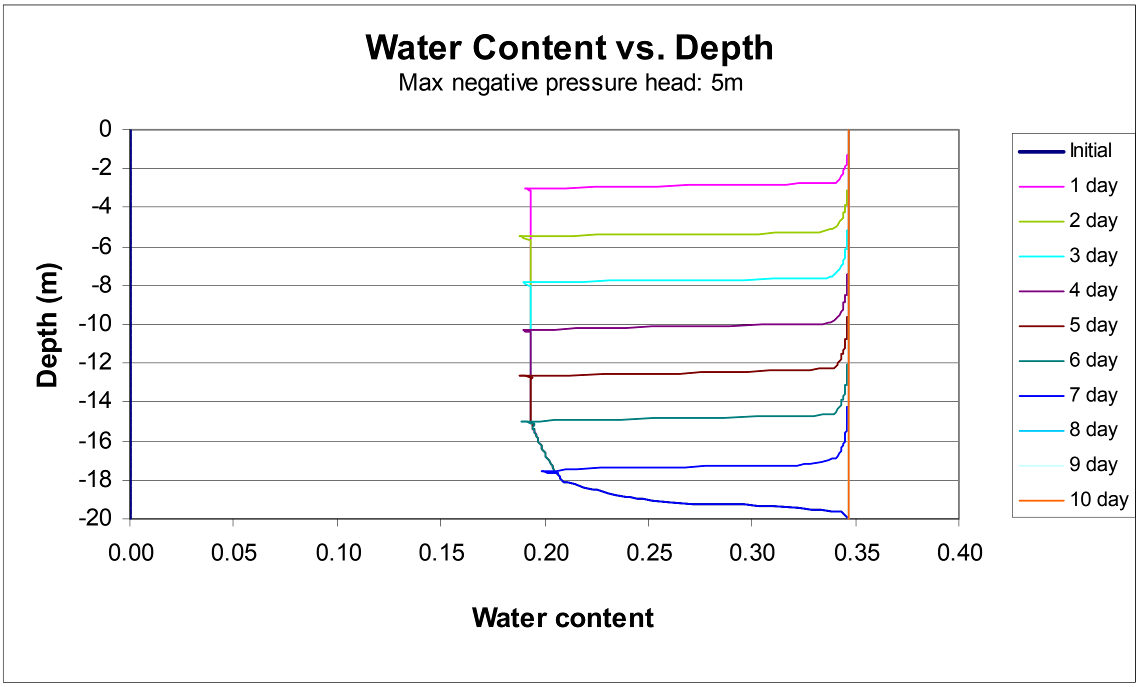


Figure A1.10 SEEP/W result showing transient of pore-pressure distribution for Case B.

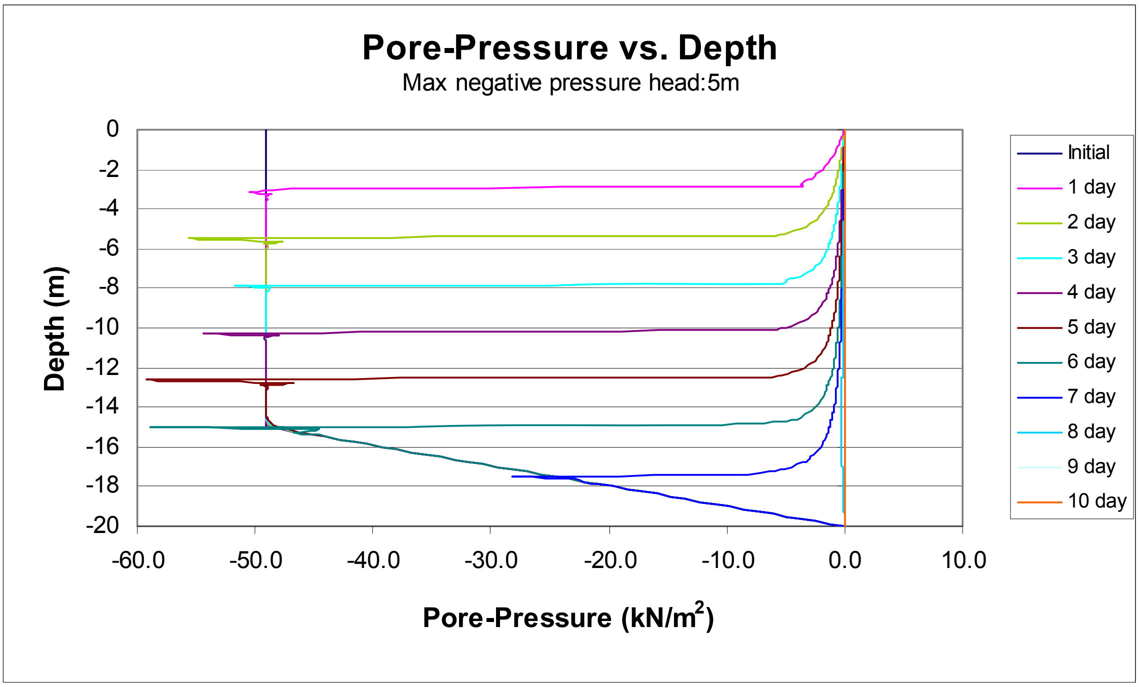


Figure A1.11 Actual and modelled increase in leachate head in a basal drainage system following cessation of leachate recirculation.

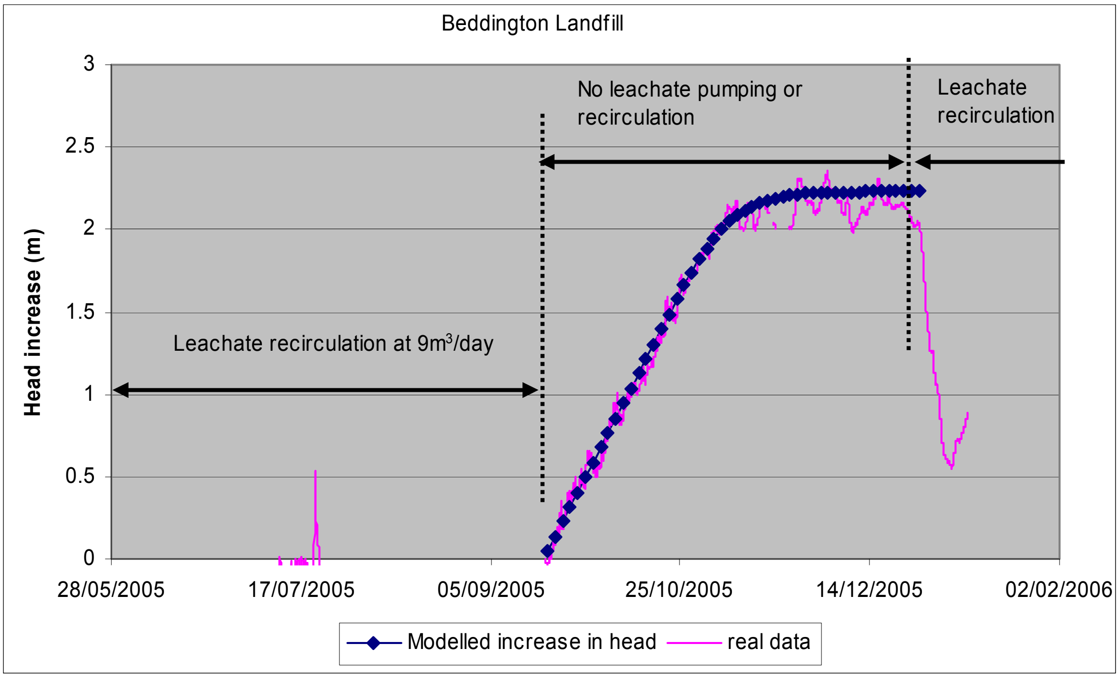
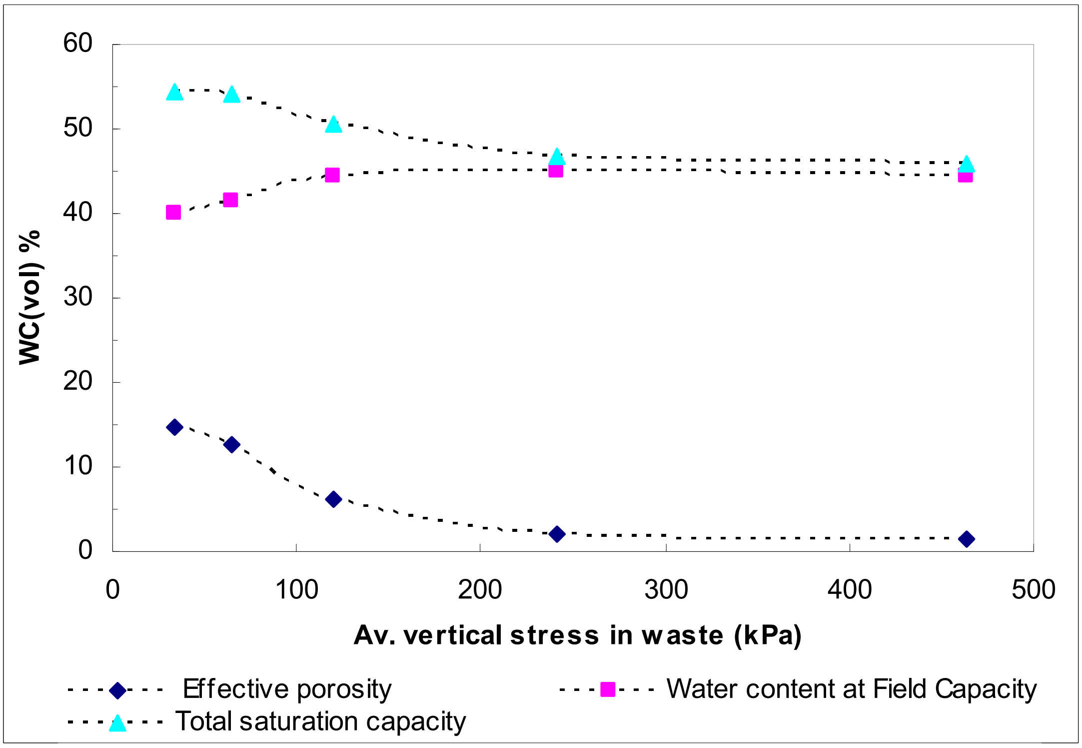


Figure A1.12 Volumetric water content versus effective stress for MSW (from Beaven, 2000).



Would you like to find out more about us, or about your environment?

Then call us on

08708 506 506* (Mon-Fri 8-6)

email

enquiries@environment-agency.gov.uk

or visit our website

www.environment-agency.gov.uk

incident hotline 0800 80 70 60 (24hrs)
floodline 0845 988 1188

* Approximate call costs: 8p plus 6p per minute (standard landline).
Please note charges will vary across telephone providers

Environment first: This publication is printed on recycled paper.